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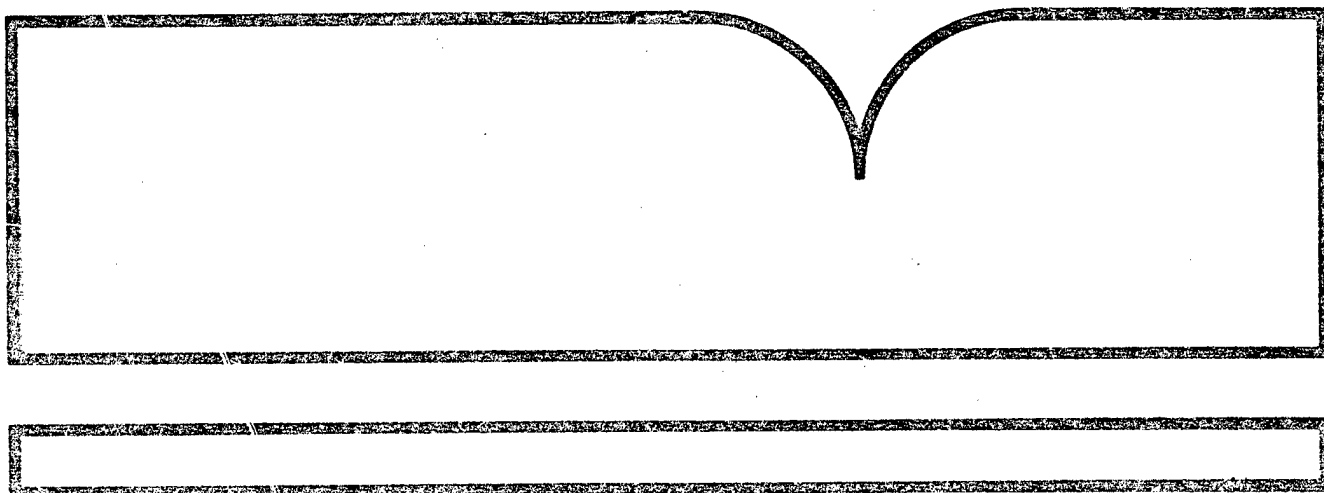
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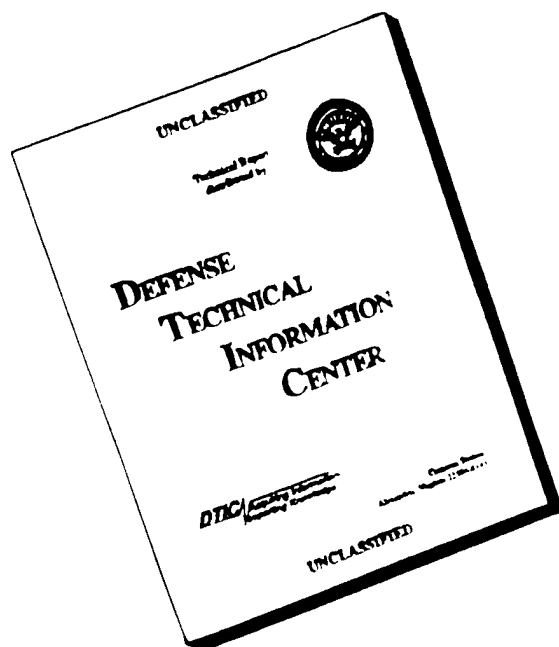
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CUTTING FORCE MEASUREMENT IN PRODUCTION
MACHINING VIA INSTRUMENTED TOOLHOLDERS

PHASE I - FINAL REPORT

John F. Pearson
Walter D. Syniuta
Nathan H. Cook

Contract No. NSF DAR-7917156

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Prepared for:

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12
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TABLE OF CONTENTS

LIST OF FIGURES.....	iii
LIST OF TABLES.....	v
LIST OF SYMBOLS.....	vi
1. SUMMARY OF PHASE I ACCOMPLISHMENTS.....	1-1
2. RECOMMENDATIONS FOR PHASE II PROGRAM.....	2-1
3. GENERAL REQUIREMENTS FOR INSTRUMENTED TOOLHOLDER DESIGN.....	3-1
3.1 Introduction.....	3-1
3.2 Discussion of Matrix Methods for Instrumented Toolholder Force Resolution.....	3-3
3.3 Brief Discussion of the Major Elements of the Instrumented Toolholder System.....	4-1
4. TRANSDUCER DESIGN.....	4-1
4.1 Optimization of Strain Gage Placement.....	4-1
4.1.1 Vertical and Horizontal Force Components, F_p and F_q	4-1
4.1.2 Axial Force Component, F_r	4-7
4.2 Analytical Model.....	4-14
4.3 Results of Analytical Model.....	4-16
4.3.1 General Considerations.....	4-16
4.3.2 Vertical and Horizontal Force Components.....	4-17
4.3.3 Axial Force Components - Configuration A.....	4-17
4.3.4 Axial Force Component - Configuration B.....	4-19
4.3.5 Axial Force Component - Configuration C.....	4-19
4.3.6 Additional Observations from Analytical Results.....	4-20
4.3.7 Conclusions from Analytical Results.....	4-21
4.4 Cost/Benefit Considerations.....	4-22
5. TRANSDUCER CONSTRUCTION.....	5-1
5.1 Description of Transducer Construction.....	5-1
5.1.1 Configuration A.....	5-1
5.1.2 Configuration B.....	5-4
5.1.3 Configuration C.....	5-4
5.2 Conclusions from Transducer Construction.....	5-4
6. PROTOTYPE SYSTEM SIGNAL CONDITIONING AND PROCESSING.....	6-1

7.	TRANSDUCER TESTING RESULTS.....	7-1
7.1	Static Calibration Procedure.....	7-1
7.2	Measured Performance during Static Testing.....	7-4
7.3	Discussion of Results of Static Testing.....	7-7
7.4	Measurement of Forces in Turning Operations.....	7-10
8.	ADVANCED SIGNAL PROCESSING.....	8-1
9.	CONCLUSIONS.....	9-1

LIST OF REFERENCES

APPENDICES

- A. DETAILED ANALYTICAL MODEL
- B. LISTING OF COMPUTER CODE OF ANALYTICAL MODEL
- C. RESULTS OF ANALYTICAL MODEL
- D. CIRCUIT DIAGRAM OF PROTOTYPE ANALOG SIGNAL PROCESSING SYSTEM

LIST OF FIGURES

FIG		PAGE
1	A Typical Toolholder for Lathe Operations.....	3-4
2a	Typical Cantilever Beam - Type Lathe Dynamometer.....	3-5
2b	Basic Toolholder Geometry.....	3-6
3	Instrumented Toolholder Prototype System Components.....	4-2
4a	Strain Gage Placement for Vertical and Horizontal Force Component Measurement.....	4-5
4b	Bridge Arrangement for Vertical Force, F_p	4-6
4c	Bridge Arrangement for Horizontal Force, F_q	4-6
5	Location of Neutral Plane for Unequal Vertical and Horizontal Force Components.....	4-9
6	Force Ratios vs. Wear Land.....	4-10
7a	Strain Gage Placement for Axial Force Component Measurement - Configuration A.....	4-11
7b	Strain Gage Placement for Axial Force Component Measurement - Configurations B and C.....	4-12
8	Prototype Instrumented Toolholder Transducer.....	5-2
9	Instrumented Toolholder System with Prototype Cabling, Shielding.....	5-3
10	Instrumented Toolholder Gage Placement Showing Axial Configuration B.....	5-5
11	Signal Conditioning and Processing Requirements.....	6-2
12	Block Diagram of Analog Matrix Manipulation for Signal Processing.....	6-3
13	Prototype Analog Signal Processing System.....	6-5
14	Instrumented Toolholder with Static Calibration Fixture Installed.....	7-2
15	Static Calibration Test Set-up.....	7-3
16	Results of Static Calibration Testing.....	7-6
17	Variation of Gage Factor and Temperature Coefficient with Temperature for Semiconductor Strain Gage Materials.....	7-8

<u>FIG</u>		<u>PAGE</u>
18	Recorded Output of Vertical and Horizontal Channels during Lathe Operations of AMTI.....	7-11
19	Recorded Output of Vertical and Horizontal Channels during Lathe Operation at AMTI.....	7-12
20	Comparison of Two-channel Outputs of Instrumented Toolholder and Cook Dynamometer during Lathe Operation at MIT.....	7-13
21	Basic Design of Digital Signal Processing System.....	7-15

LIST OF TABLES

TABLE

PAGE

1. Results of Influence Matrix Calculations for Axial Gage Placement
Options A, B and C4-17a
2. Calculation of Physical Crosstalk for Three Force Components, for
Axial Gage Placement Options A, B and C4-18
3. Measured Performance - Static Testing7-5

LIST OF SYMBOLS

<u>Symbol</u>		
a	y-coordinate of cutting point M	in
$a_{11}, a_{12}, \dots, a_{33}$	coefficients relating strains to forces	
A_{csx}	crosssectional area of toolholder	in ²
b	base of toolholder shank	in
$b_{11}, b_{12}, \dots, b_{33}$	influence coefficients relating channel outputs to forces	
$b'_{11}, b'_{12}, \dots, b'_{33}$	coefficients relating forces to channel outputs	
$[B]$	matrix of b'_{ij} coefficients above	
c	x-coordinate of cutting point M	in
E	modulus of elasticity	bf/in ²
$[F]$	matrix of force components	lbf
F_p, F_q, F_r	vertical, horizontal and axial force components	lbf
FS	full-scale (abbreviation)	
h	height of toolholder shank	in
I_{xx}, I_{yy}	moment of inertia about x and y-axes	in ⁴
l	distance from cutting point M to gage sites	in
L	distance from cutting point M to clamping plane	in
M_x, M_y, M_z	bending moments about x, y, z-axes	lbf
P	power dissipation	watt
P_1, P_2	points defined by Fig. 5	

R	electrical resistance	ohm
RTO	referred to output (abbreviation)	
S	gage factor (abbreviated GF)	
V_1, V_2, V_3	matrix of channel outputs	
$[V]$	channel outputs	volt
V_{b1}, V_{b2}, V_{b3}	bridge excitation voltages	volt
$V_{out 1}, V_{out 2}, V_{out 3}$	bridge output voltages	volt
x, y, z	coordinates of Cartesian system	
β	angle of inclination of neutral plane	degree
ϵ_n	strain at position n	

1. SUMMARY OF PHASE I ACCOMPLISHMENTS

The primary objective of Phase I research program was to demonstrate the feasibility of instrumenting a standard lathe toolholder with strain gages as a means of producing a low-cost cutting force transducer.

The two tasks identified as critical in this proof-of-concept program were

1. Develop a strain gage mounting scheme which would maximize sensitivity and permit isolation of individual force components.
2. Develop signal conditioning and processing methods to interface the instrumented toolholder with the variety of likely applications.

A gage mounting scheme was developed which provided suitable sensitivity and force component isolation. A computer analysis was performed to investigate the validity of this methodology and to model three proposed prototype configurations. Analytical results indicated that any of the three would result in a successful transducer design.

A prototype was constructed which followed the analytical model within the constraints of size. This initial model was tested and found acceptable for the measurement of vertical and horizontal force components. The axial measurement showed considerable thermal instability. The gage mounting scheme for measuring axial force was modified to reduce thermal drift. This second version showed greatly improved thermal performance, though still falling short of system design requirements.

A series of calibration tests were performed to establish system

sensitivity and linearity. These tests resulted in excellent sensitivity and linearity in the vertical and horizontal directions.

A series of lathe cutting tests were performed to establish the functionality of the Instrumented Toolholder System. Measurements made on a standard lathe and in conjunction with a research dynamometer verified that the system operated in a reliable and adequate fashion.

Several options for system applications were defined which included force monitoring and input to a computer-numeric-controlled system. A signal conditioning/processing scheme was identified for each of these options. Preliminary design considerations were established which outline the requirements for these options.

2. RECOMMENDATIONS FOR PHASE II RESEARCH

The Phase I feasibility research established that it is possible to obtain accurate cutting force measurements with a standard toolholder by using conventional strain gages with appropriate signal processing. Further research is required in four main areas before the technique can be applied as a practical tool wear measurement system. The major research tasks are as follows:

1. Develop Practical Transducer Design Techniques: In addition to solving the problem of measuring axial forces with the same level of precision and sensitivity as the horizontal and vertical forces, the gaging technique must be ruggedized without excessive loss of sensitivity and accuracy so that the instrumented toolholder can withstand the rigors of industrial use. This work should be brought to the stage where a ruggedized prototype can be tested in an actual industrial environment.
2. Define Correlation Techniques: In order for a practical system to result from the proposed research, the information obtained in the cutting force signals must be translated into the desired knowledge about the tool/workpiece system. Out of the large number of correlations available, e.g., absolute force levels, ratios of two or three force components, etc., the one or two techniques that hold the most promise in terms of accuracy, widespread applicability, cost effectiveness, etc., should be identified and appropriate information processing techniques should be developed.

3. Identify Interface with NC Machines: While it is generally acknowledged that knowledge of cutting conditions is necessary for adaptive control of NC machines, it is not clear how the NC machine should utilize this information, nor how interface should be defined. While there is probably no unique answer to this question, one or more promising adaptive control applications should be identified and researched in order to establish that tool force measurement can indeed provide useful input to adaptive control machining.
4. Field Test Tool Force Measurement System: The outputs of the first three tasks should be tested through field evaluation of a prototype system employing a ruggedized, instrumented toolholder (Task 1), a prototype signal processing package (Task 2), to provide input for adaptive control of a CNC control machining system (Task 3).

3. GENERAL REQUIREMENTS FOR INSTRUMENTED TOOLHOLDER DESIGN

3.1 Introduction

An important national problem is the slipping productivity in the U.S. relative to other countries. Computer controlled machining is fast becoming a larger part of small batch manufacturing machining capacity. The next step beyond this phase, which can provide a tremendous improvement in productivity, and result in energy and material conservation is "adaptive control" machining. However, this step would require the development of an inexpensive innovative approach to measurement of cutting tool forces. The force components can then be fed back to the computer and used to optimize the machine process.

The major force components acting on a cutting tool vary in magnitude, phase, and ratio according to many conditions such as: flank wear, sharpness of the cutting edge, workpiece rigidity, cooling effectiveness, etc. A reliable, inexpensive, non-obtrusive, non-invasive production-type tool

force sensor would provide the missing link required for adaptive control machining. Furthermore, even without adaptive control, the output of such a sensor can be used to monitor tool wear, breakage, workpiece condition, etc., and thus can provide important benefits in and of itself.

The forces involved in metal-cutting operations have been measured for many years by those involved in cutting research. It has been clear that monitoring cutting forces can provide signals rich in information on tool condition, vibration, tolerance, machine utilization, etc. However, the use of cutting force measurement in production control has been severely limited due to the nature of the force dynamometers available. Most dynamometers are primarily suited to research activity and do not have the operational flexibility or low cost required for use in a general purpose machining environment; i.e., it is not practical to interpose an extra electro-mechanical device between the machine structure and the cutting tool.

A satisfactory production-oriented dynamometer must be such that it in no way interferes with the "normal" operation of the machine-tool. Conceptually, some part of the standard machine structure could be instrumented in a manner to give force information. This, if possible, would have to be done by a machine-tool builder.

In recent years, there has been a growing tendency to use some form of "toolholder" between the machine-tool and the actual cutter. In turning operations, for instance, the common practice is to employ a toolholder which supports disposable cutting inserts of tungsten-carbide, ceramic,

other tool material. Fig. 1 shows a typical lathe toolholder.

The goal of the Phase I research has been to explore the feasibility of the instrumented toolholders to serve as cutting force dynamometers. This method will provide the necessary force signals while permitting normal operation of the machine/tool system.

3.2 Discussion of Matrix Methods for Instrumented Toolholder Force Resolution

In order to appreciate the design problems, consider a typical cantilever beam-type two-force component lathe dynamometer as shown in Fig. 2a. The design is such that the point of force application lies on the neutral axis of the beam (z-axis). Gages are placed symmetrically on four sides of the beam to measure moments about the X and Y axes, and therefore the forces producing those moments. Because the point of force application is on the Z axis, the moment about the X axis is due only to F_p and that about the Y axis to F_q , and F_r has no effect at all.

Fig. 2b shows the geometry associated with most standard lathe toolholders; the point of force application (M) is offset from the Z axis by a and c. In this instance the radial force F_r affects M_x and M_y ; and both F_p and F_q apply twisting moments about the Z axis. Thus, any strain gages applied to the toolholder will be sensitive to at least two of the applied forces.

Theoretically, 3 strain gages randomly placed on a toolholder would provide enough information to determine the force components. However, from

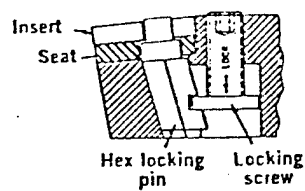
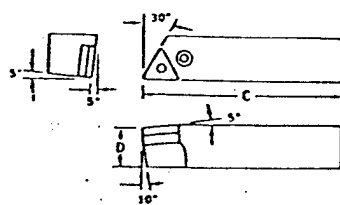
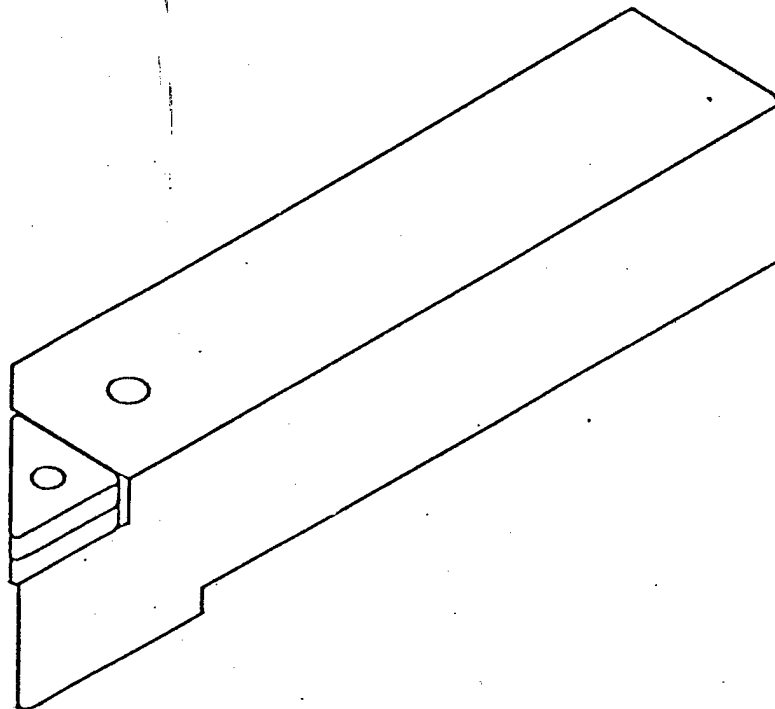


FIGURE 1: A TYPICAL TOOLHOLDER
FOR LATHE OPERATION

3-Component Dynamometer

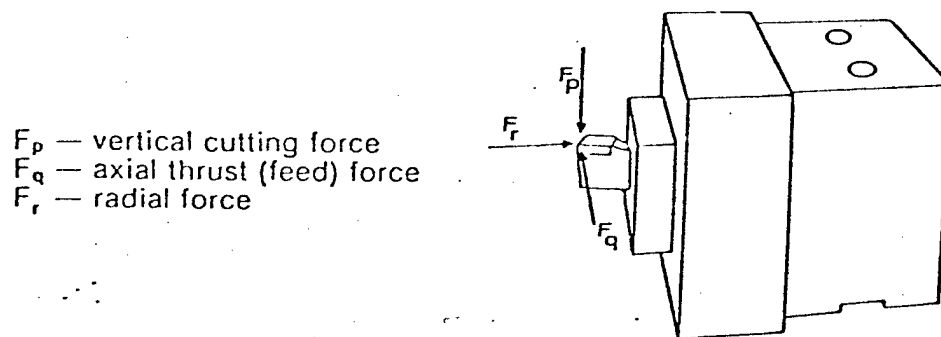


FIGURE 2a: TYPICAL CANTILEVER BEAM-TYPE
LATHE DYNAMOMETER

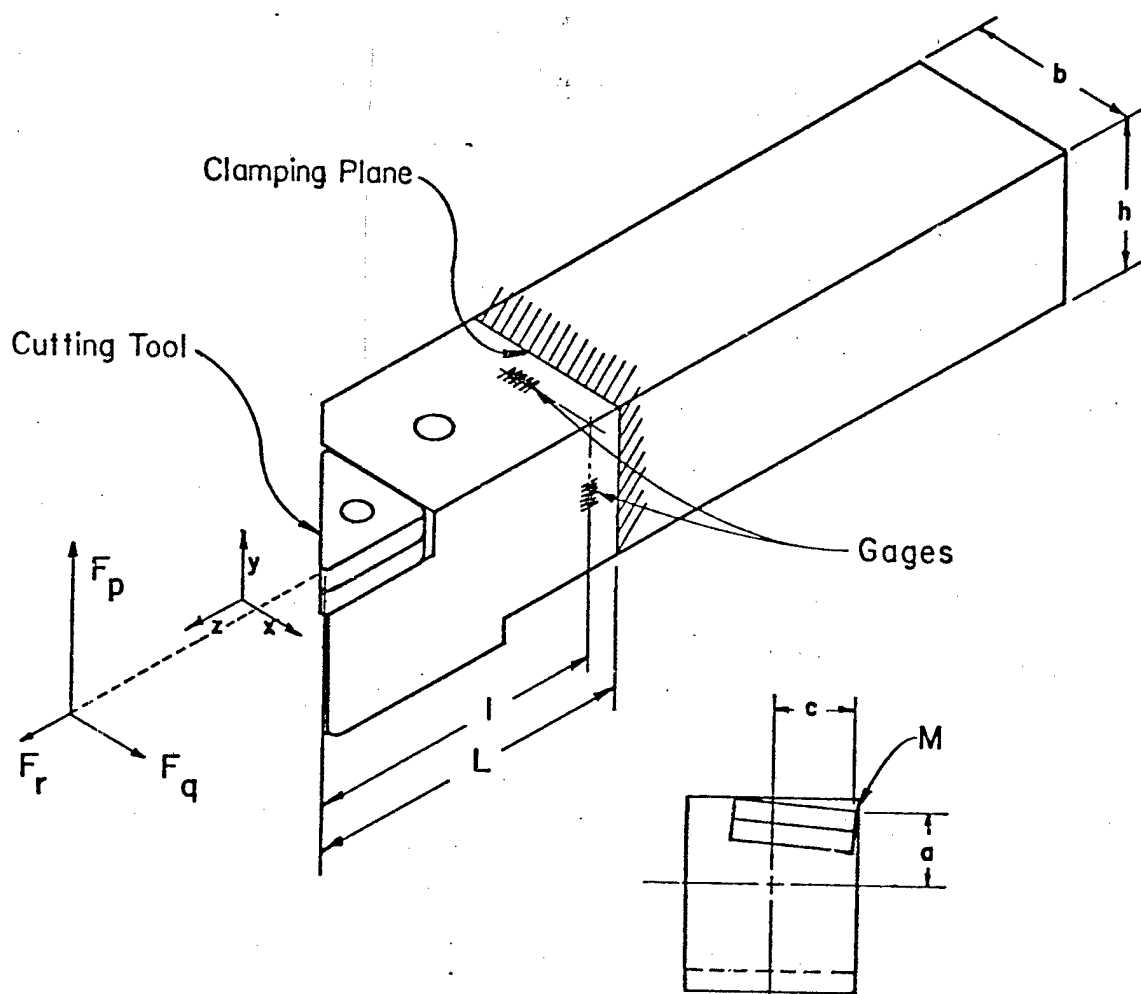


FIGURE 2b: BASIC TOOLHOLDER GEOMETRY

a practical point of view, we know there must be an optimal set of gage locations which will give the least overall error.

In order to use such a device, we will have to determine an influence-matrix that defines this relationship between each output and each force component. To express this analytically, if the three desired force components are F_1, F_2, F_3 ; and the three strain gage readings are V_1, V_2, V_3 , then we can reasonably assume a linear relationship such that:

$$F_1 = b_{11}V_1 + b_{12}V_2 + b_{13}V_3$$

$$F_2 = b_{21}V_1 + b_{22}V_2 + b_{23}V_3$$

$$F_3 = b_{31}V_1 + b_{32}V_2 + b_{33}V_3$$

or

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = [B] \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

where $[B]$ is the influence-matrix:

$$b_{11} \quad b_{12} \quad b_{13}$$

$$b_{21} \quad b_{22} \quad b_{23}$$

$$b_{31} \quad b_{32} \quad b_{33}$$

For an ideal dynamometer (such as we build for research purposes) only the main diagonal terms (b_{11}, b_{22}, b_{33}) are significant, the others being essentially (and desirably) zero. For the instrumented toolholder, it will not be possible for all off diagonal terms to be zero. However, with optimal

gage location, we are able to make the diagonal terms dominant so that when the matrix multiplication is carried out, the inevitable measurement errors will not affect the system accuracy significantly.

3.3 Brief Discussion of the Major Elements of the Instrumented Toolholder System

A brief description of the instrumented toolholder system follows. In Figure 3 the three basic elements of the instrumented toolholder force transducer are illustrated. The first element, the prototype toolholder device is instrumented with strain gages and generates low level output signals. The second element is a signal conditioner which provides bridge excitation voltage to the toolholder strain gages and amplifies the bridge output signals such that the resultant force signals are ready for matrix manipulation. The third and final element is the analog electronic circuit which performs the matrix manipulation and directly displays the horizontal, vertical and radial forces which have been applied to the instrumented toolholder. Digital indication of three orthogonal forces can be displayed in real time to give a lathe operator visual indication of the work which his lathe tool bit is performing.

4. TRANSDUCER DESIGN

In this section we shall address the design of the prototype instrumented toolholder. We shall begin by looking at strain gage mounting schemes which will permit high sensitivity and force-component measurement

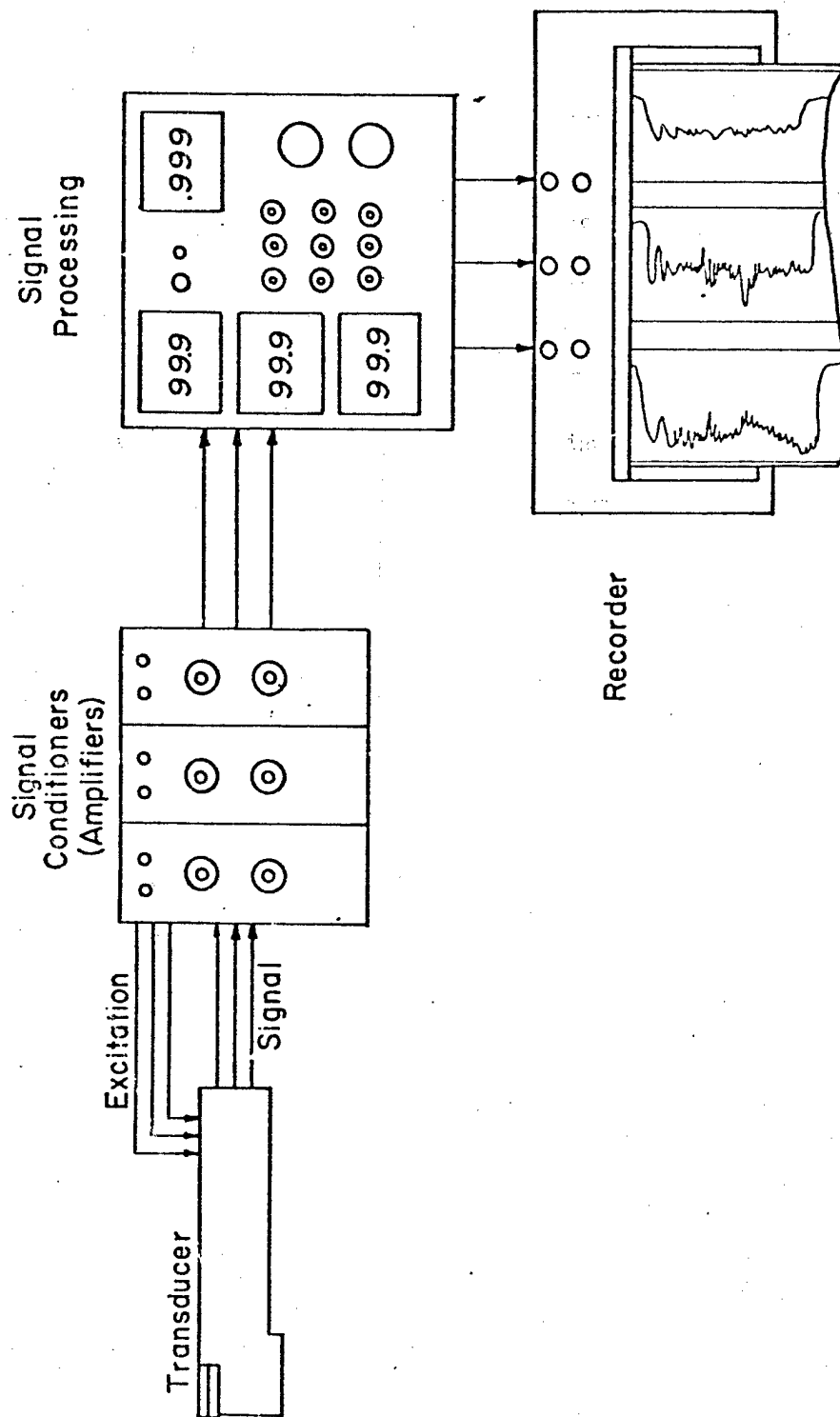


FIGURE 3: INSTRUMENTED TOOLHOLDER
PROTOTYPE SYSTEM COMPONENTS

isolation (Thus minimizing the off diagonal terms in the influence matrix.). This methodology will permit us to generate a set of gage positions to satisfy the design criteria of maximum sensitivity and force component isolation. These gage locations will then permit the development of an analytical model for predicting transducer performance.

4.1 Optimization of Strain Gage Placement

Figure 2b represents a typical toolholder for a turning process. The cutting point M experiences a force which can be resolved into three orthogonal components, F_p , F_q and F_r . The toolholder is clamped in a tool post a distance L from the cutting point.

4.1.1 Vertical and Horizontal Force Components, F_p and F_q

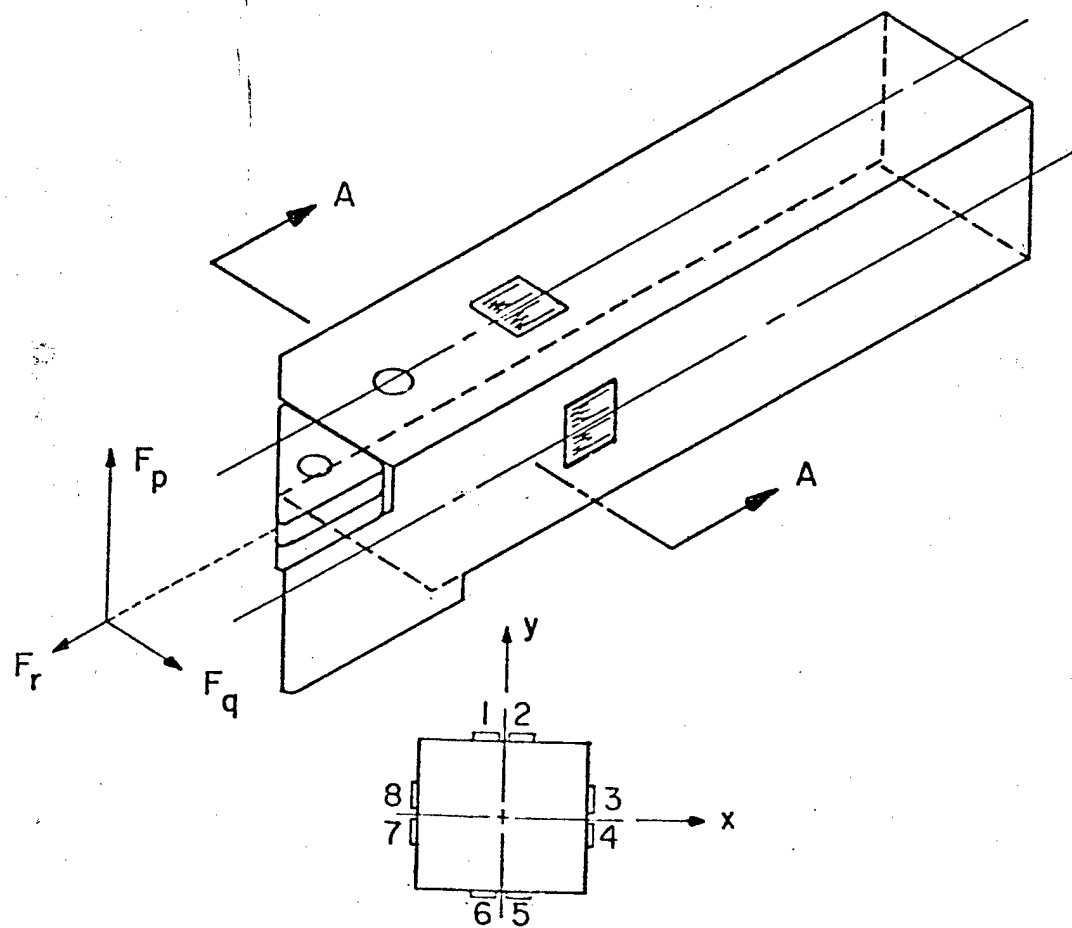
Some conclusions about optimizing strain gage location for force measurement can be reached through some simple observations. First of all, in order to choose a location which will maximize sensitivity to F_p and F_q , the mounting locations should be as far from point M as possible, i.e., as near to the clamping plane as possible. However, it is important to consider the end effects of the clamping apparatus.

Secondly, in order to measure the vertical component of force, F_p , gages should be placed on the horizontal surface. These bending moments caused by F_p result in the greatest longitudinal strains and, hence, highest measurement sensitivities. Similarly, gages for measuring the horizontal component of force, F_q , should be placed on the vertical planes, where longitudinal strains due to F_q are maximum.

These fundamental considerations lead directly to a scheme for strain gage placement which will optimize measurement of F_p and F_q . With reference to Figure 4a, we note that F_p , the vertical component of force can be most easily sensed by strain gages 1, 2, 5 and 6 located on the horizontal surface. The bridge arrangement of Figure 4, Bridge 1, shows how the strain gages form a four-arm bridge. Similarly, we note that F_q , the horizontal component of force can be best sensed by strain gages 3, 4, 7 and 8 located on the vertical surface. The bridge arrangement of Figure 4b and 4c shows how these strain gages form a four-arm bridge. The Wheatstone bridge configurations shown in Figure 4 provide both maximum strain sensitivity and maximum thermal compensation.

Based on this strain gage placement scheme we can analyze the effect of the horizontal force, F_q on the vertical force strain gages. If the gages are mounted symmetrically with respect to the vertical axis, bending moments due to F_q cause a positive strain at gages 2 and 5 and a negative strain of equal magnitude at gages 1 and 6. This change in Bridge 1 causes no net output. This configuration allows Bridge 1 to measure strains caused by F_p alone, while Bridge 2 will indicate only F_q . Crosstalk between F_p and F_q will be present only due to gage mounting inaccuracies.

The effect of the axial force on the horizontal and vertical force strain gages will be small since the magnitude of F_r is small compared to F_p and F_q ($\sim 1/4$) and since a and c (Figure 2b) are small compared to 1 ($\sim 1/3$). Thus the resulting imbalance on bridges 1 and 2 due to F_r will be small ($\sim 1/12$) compared to the imbalance resulting from F_p and F_q .



SECTION A-A

FIGURE 4a: STRAIN GAGE PLACEMENT FOR
VERTICAL AND HORIZONTAL
FORCE COMPONENT MEASUREMENT

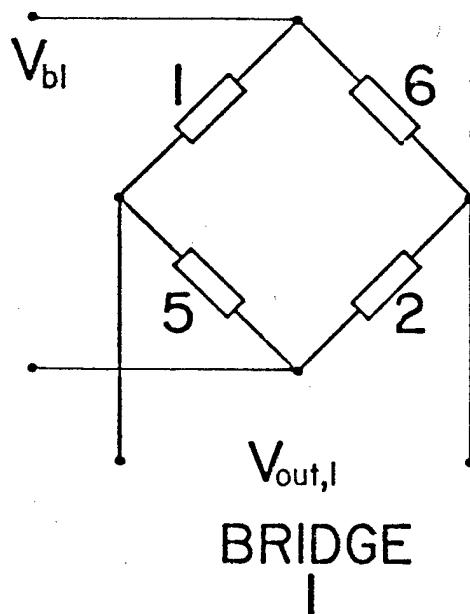


FIGURE 4b: BRIDGE
ARRANGEMENT FOR
VERTICAL FORCE, F_p

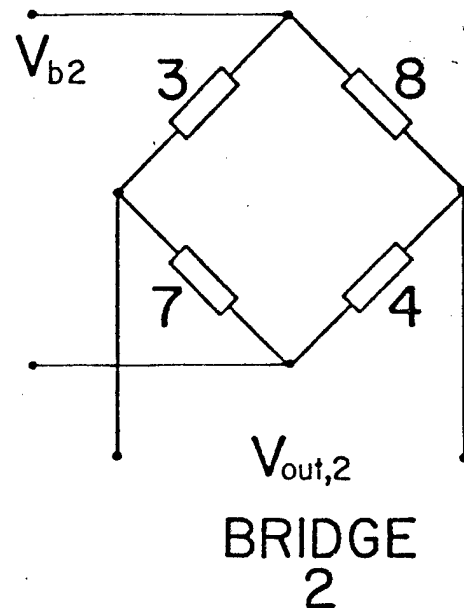


FIGURE 4c: BRIDGE
ARRANGEMENT FOR
HORIZONTAL FORCE, F_q

4.1.2 Axial Component, F_r

Next, consider the placement of gages to measure the radial force component, F_r . Because there is no mechanical advantage to amplify the radial strains, this signal is the smallest in magnitude. It is subject to influence from the two orthogonal forces F_p and F_q and therefore is the most difficult to measure. The question is thus raised: Where can strain gages be placed which will maximize sensitivity to F_r and minimize the crosstalk from F_p and F_q ?

One obvious possibility for minimizing cross effects is to place gages near as possible to point M, thereby minimizing the moment arms for F_p and F_q . However, near point M possibilities are greatest for physical contamination from metal chips and lubricating oil, high temperatures and impact damage. In addition, since lead wires must be run from the gages out of the toolholder, one axial location for gage placement would be advantageous. Therefore, given these considerations, where might gages be located a distance l from the cutting point which would minimize effects of F_p and F_q ?

We know from simple analytical considerations that a plane exists along which the displacement due to bending moments induced by F_p and F_q is zero. Furthermore, it can be shown [1] that this plane is inclined on angle β from the horizontal axis where

$$\tan \beta = \frac{F_q}{F_p} .$$

4-1

Figure 5 illustrates this neutral plane location. From Eq. 4-1 we can see that the location of zero strain due to bending moments is a direct function of the ratio F_q/F_p . If a strain gage were located at the intersection of this neutral plane and a vertical surface (points P_1 and P_2), it would not be sensitive to strains induced by F_p and F_q . Therefore, it could be used to measure compressive strain due to axial force F_r alone.

Next, let us determine the location of Points P_1 and P_2 . Eq. 4-1 shows us that we must know the force ratio F_q/F_p if we are to locate these points. Fig. 6 shows a typical example of this force ratio as a function of tool wear. We can see that (F_q/F_p) varies from about 0.4 to 0.5 over the range of tool wear illustrated. If we were to locate a strain gage at the position corresponding to $F_q/F_p = 0.5$, the effects on that gage due to F_p and F_q would diminish over tool life. So, as tool wear increased, our crosstalk effects would decrease by about 20% over the range of tool wear illustrated. Thus, the effectiveness of our matrix methods would increase as tool wear progresses. We conclude that the gages for measuring the axial force component should be located at points P_1 and P_2 where $\tan \beta \approx 0.5$.

Figure 7a-b illustrates the strain gage locations for sensitivity to F_r which arise from the above considerations. In order to maximize system sensitivity and minimize error due to temperature effects, complete four-arm bridges should be used. However, in the case of this radial component (a pure compressive load) a four-arm bridge of axial gages would yield zero output. Three options were considered for this measurement.

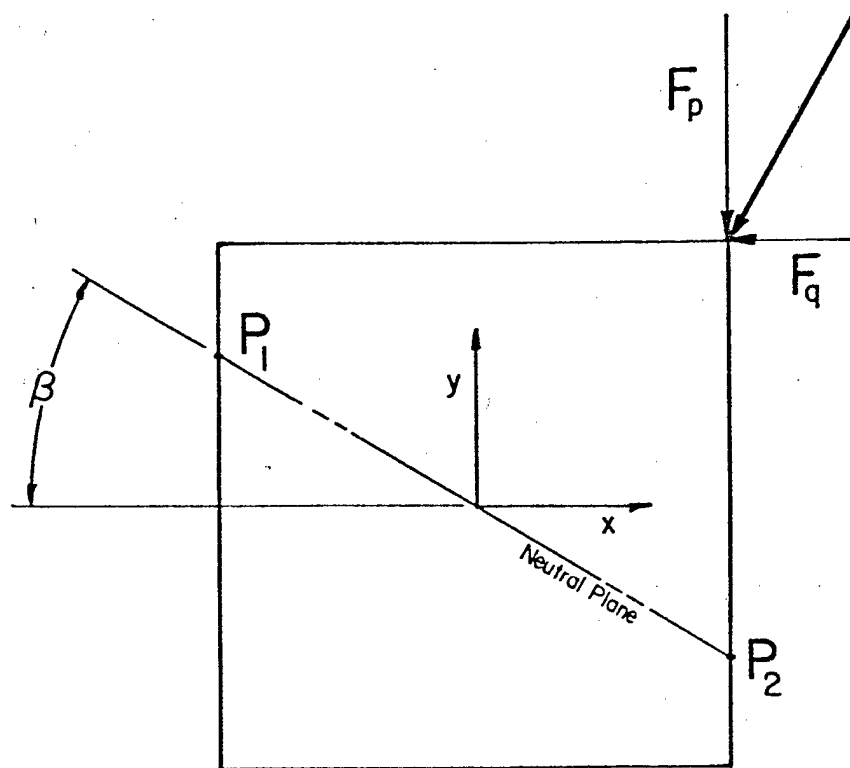


FIGURE 5: LOCATION OF NEUTRAL PLANE
FOR UNEQUAL VERTICAL AND
HORIZONTAL FORCE COMPONENTS

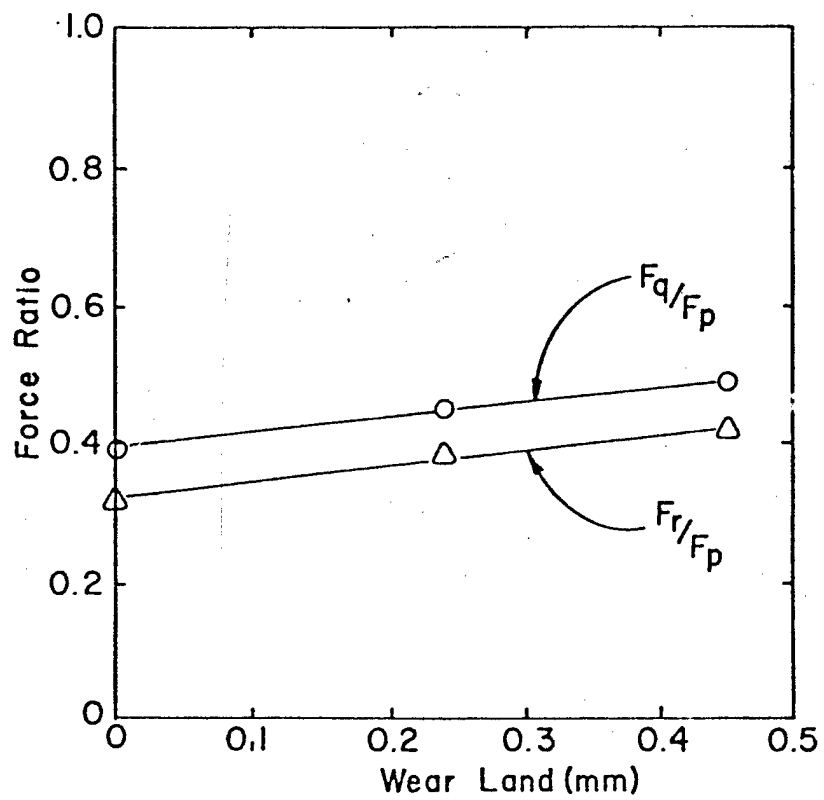
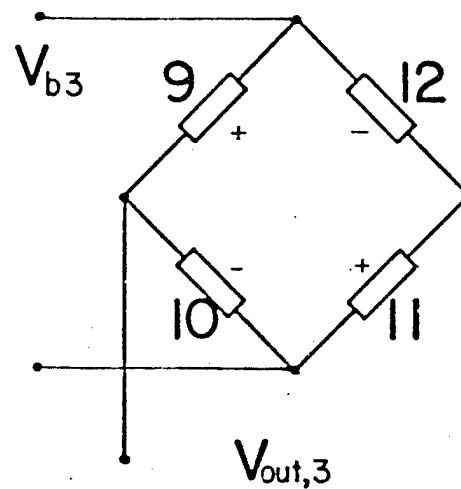
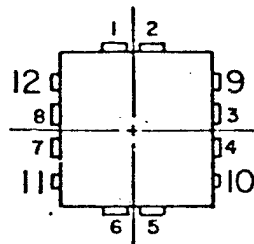
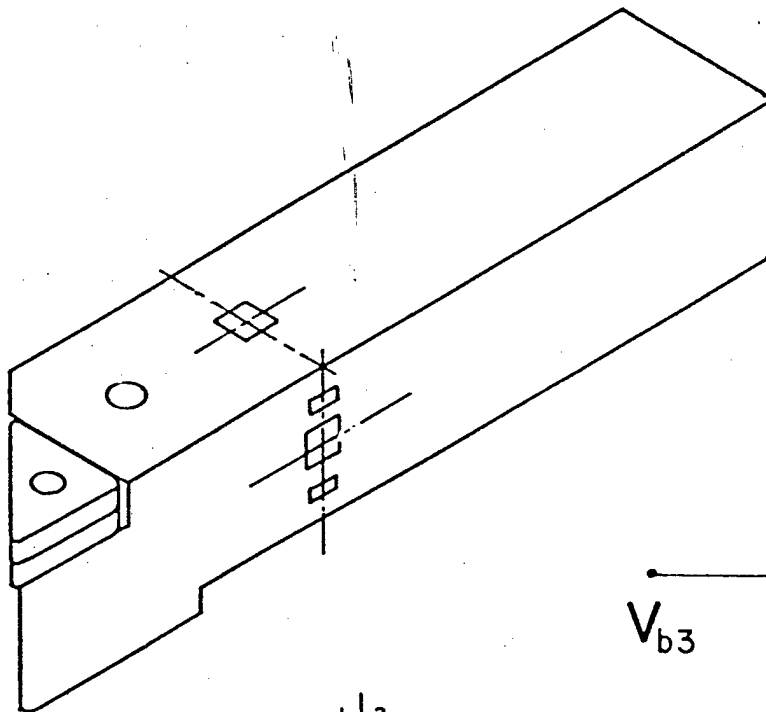


FIGURE 6: FORCE RATIO VERSUS
WEAR LAND [2]



BRIDGE
3

FIGURE 7a: STRAIN GAGE PLACEMENT
FOR AXIAL FORCE COMPONENT
MEASUREMENT CONFIGURATION A

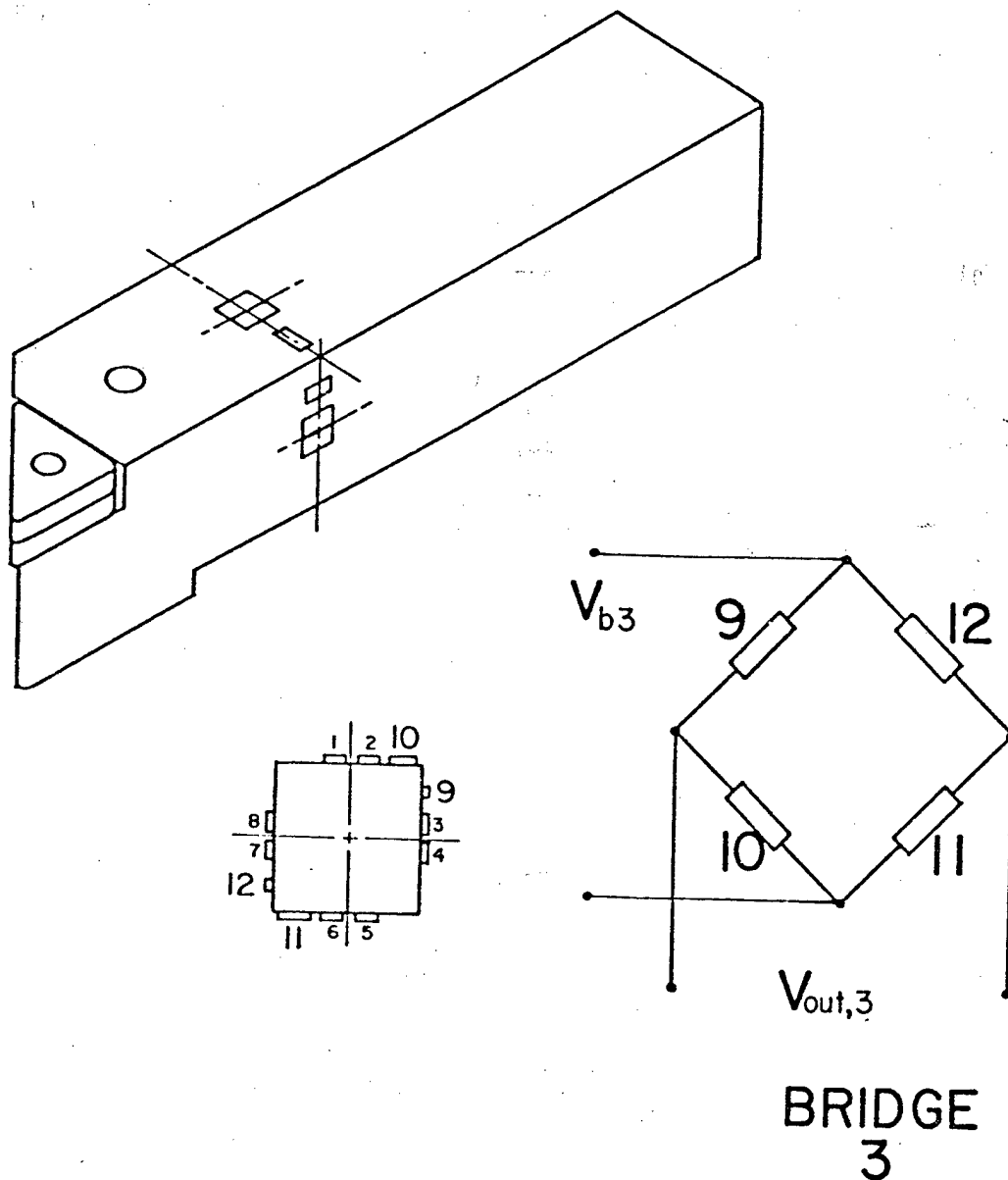


FIGURE 7b: STRAIN GAGE PLACEMENT
FOR AXIAL FORCE COMPONENT
MEASUREMENT CONFIGURATIONS B AND C

They are described below.

Configuration A

Four axial semiconductor gages, using two negative and two positive strain sensitivities (Fig. 7a). This configuration represents the highest potential strain sensitivity, since it allows the use of a full bridge with high strain sensitivity and potential temperature compensation. However, the peculiarities of semiconductor gage characteristics make this an unworkable solution. (Refer to Section 7.2 for a discussion of the problems encountered with this measurement scheme.)

Configuration B

Four N type semiconductor gages mounted on the toolholder with two located along and two located normal to the axis of the toolholder. See Figure 7b. This configuration yields slightly decreased sensitivity over a half-bridge configuration due to the added Poisson effect in the direction perpendicular to the longitudinal axis under compressive loading. In addition, this configuration allows bridge self-temperature compensation. The disadvantage of this configuration is the relatively high cost of semiconductor gages.

Configuration C

Four high resistance foil strain gages mounted in a configuration similar to B. That is, two gages mounted along the toolholder axis and two mounted normal to the toolholder axis. High

gain electronics are necessary to achieve the required sensitivities (approximate gain of 10,000).

4.2 Analytical Model

We have seen in Sec. 3.2 that, in general, the outputs of three randomly positioned strain gage bridges are sufficient to determine three orthogonal components of force. In addition, we can define a set of influence coefficients (b_{ij}) such that

$$\begin{bmatrix} F_P \\ F_Q \\ F_R \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad 4-2$$

This equation shows that once the coefficients (b_{ij}) have been determined, a unique relationship has been defined relating force inputs to bridge outputs. This technique provides a simple method for measuring the three components of cutting force.

In Sec. 4.1 we found that one could identify strain gage positions which would make each bridge sensitive mainly to one force component and only minimally affected by the other two. That is, we can position the gages so that the diagonal terms of the B-matrix (b_{11} , b_{22} , b_{33}) are large in comparison to the off-diagonal terms. We have identified a series of gage positioning options to implement these techniques.

In this section we shall present a summary of the analytical model for predicting the values of (b_{ij}) given toolholder geometry and gage positions.

In the Appendix A the reader can find a detailed treatment of this model for one of the options of Sec. 4.1.2.

To begin with, we can model the toolholder of Fig. 2b as a cantilever beam clamped a distance L from the cutting point M. This beam is loaded at M by three orthogonal force components F_p , F_q and F_r . We can then calculate the resulting twelve strains ($\epsilon_1 - \epsilon_{12}$) at each gage site. The result of this analysis is an expression relating each strain to the three force inputs which has the form

$$\epsilon_n = a_{n1} F_p = a_{n2} F_q + a_{n3} F_r. \quad 4-3$$

We know that for small strains, the output of the Wheatstone bridges of Sec. 4 can be expressed by a linear summation of each gage output. For example, for Bridge 1 of Fig. 4b, we can write

$$V_{out, 1} = F_{b1} (S_1 \epsilon_1 + S_2 \epsilon_2 - S_5 \epsilon_5 - S_6 \epsilon_6) \quad 4-4$$

Where:

V_{b1} = bridge excitation voltage

S_1 = gage factor for gage 1, etc.

ϵ_1 = strain at gage site 1, etc.

By combining Eq. 4-3 and 4-4, we arrive at an expression which can be reduced to the form

$$V_1 = b'_{11} F_p + b'_{12} F_q = b'_{13} F_r \quad 4-5$$

or, in matrix form

$$[V] = [B] [F] . \quad 4-6$$

So, we see that Eq. 4-6 represents a unique linear relationship between three force inputs (F_p , F_q , F_r) and three bridge outputs (V_1 , V_2 , V_3). By premultiplying each side of Eq. 4-6 by B^{-1} , we find

$$[F] = [B]^{-1} [V] . \quad 4-7$$

Eq. 4-7, then, is the expression identical to Eq. 4-2 which allows us to calculate unique values for F_p , F_q and F_r from V_1 , V_2 and V_3 once the influence coefficients (b_{ij}) have been determined. Using these results, then, we can analytically predict transducer sensitivity from a stress analysis of a particular toolholder and gage geometry.

4.3 Results of Analytical Model

4.3.1 General Considerations

In the preceding section we outlined an analytical model for predicting transducer performance. This model was used to analyze trial configurations and to select proper strain gage materials. The model was implemented as a computer program to allow rapid analysis of various trial configurations. The complete FORTRAN listing of this coding may be found in Appendix B.

As we have seen in previous sections, the scheme for measuring vertical and horizontal force components was fairly straightforward. The configuration shown in Fig. 4 was used in all trial cases. The axial component measurement scheme was then varied to assess the performance of Configurations A, B

and C described in Sec. 4.1.2. The input parameters were transducer geometry, strain gage positioning, strain gage properties and signal conditioning parameters. The outputs of the program were strains at each gage site, and calculated influence coefficients (b_{ij}).

A summary of these calculations is presented in Table 1 for the three types of axial force measurement (the reader is referred to Appendix C for a complete tabulation of these results). The data shown are calculated values for the influence coefficients introduced in Sec. 4.3. That is, these numbers represent the scaling factors for isolating one force component signal from the effects of the other two. Table 2 presents a reduction of these raw influence coefficients to values suitable for comparison to each other and for performance evaluation.

4.3.2. Vertical and Horizontal Force Components

Let us first consider the vertical and horizontal force component measurement. From Table 2 we can see that, in all cases, the sensitivity to force inputs is 20.9 V/lb. If we are to assume that random system noise can be limited to less than 10 mV, we find that inputs of 1 lb magnitude can be distinguished. Therefore, we can resolve forces on the order of 100 lb to within 1 lb. This accuracy is more than sufficient for normal machine tool applications.

4.3.3 Axial Force Component - Configuration A

We first reiterate that Configuration A consists of four semiconductor gages using two negative and two positive strain sensitivities. The results

$$\begin{bmatrix} F_p \\ F_q \\ F_r \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

Axial Configuration	Excitation Voltage	Gage Type	Gage Factor	Amplifier Gain (V/V)	Influence Coefficients Matrix	- [B]
A	3.5	Semiconductor	2-(+100)	1000	-47.9	0
			2-(-100)		0	6.94
B	3.5	Semiconductor	4-(-100)	1000	-47.9	0
					0	11.0
C	15	Foil	4-(2.0)	10,000	-47.9	0
					0	9.57

Vertical and Horizontal Conditions: Four Foil Gages
 Bridge Excitation Voltage = 5.0 V
 Gage Factor = 2.0
 Amplifier Gain = 2000 V/V

TABLE 1: RESULTS OF INFLUENCE MATRIX CALCULATION FOR TRANSDUCER CONFIGURATIONS A, B and C

Conditions

Force Input: 100 lb

<u>Gaging Configuration</u>		<u>Sensitivity</u> (mv/lb)	<u>Physical Crosstalk before Influence Coefficients</u> (%)		
			<u>Vertical</u>	<u>Horizontal</u>	<u>Axial</u>
A	Vertical	20.9	--	0	-14.5
	Horizontal	20.9	0	--	17.3
	Axial	32.4	0	0	--
B	Vertical	20.9	--	0	-23.0
	Horizontal	20.9	0	--	27.3
	Axial	20.4	0	0	--
C	Vertical	20.9	--	0	-20.0
	Horizontal	20.9	0	--	23.8
	Axial	23.5	0	0	--

TABLE 2: CALCULATION OF PHYSICAL CROSSTALK FOR THREE FORCE
COMPONENTS, FOR INSTRUMENTED TOOL HOLDER
CONFIGURATIONS A, B AND C

presented on Table 2 clearly show that Configuration A presents the best potential for sensitive axial force measurement. The sensitivity (32.4 mv/lb) is even greater than the vertical and axial cases. Furthermore, the physical crosstalk is the lowest of the cases analyzed (14.5-17.3%). So, if this configuration could be physically implemented, it would provide an excellent axial force measurement. However, it bears the disadvantage of the high cost of the four semiconductor strain gages.

4.3.4 Axial Force Component - Configuration B

Configuration B represents two axial and two perpendicular N type semiconductor strain gages mounted on the toolholder. It is another viable alternative for axial component measurement. In comparison to Configuration A, it shows both reduced sensitivity to force input and increased physical crosstalk. However, the sensitivity remains on the same order as the vertical and horizontal channels. The crosstalk, though high, remains in the acceptable range. That is, even if the error in implementing the influence coefficients were as high as 10%, the total error in indicated axial force would be no greater than about 3%. However, Configuration B shows no technical advantage over the configuration using standard foil strain gages. Since semiconductor gages are about five times as costly as foil gages, Configuration B would add about \$30 to the manufacturing cost of the transducer while adding no increase in performance.

4.3.5 Axial Force Component - Configuration C

Configuration C is the same geometry as Configuration B but using high resistance foil gages. We can see from Table 2 that like Configuration B,

Configuration C offers decreased sensitivity and increased crosstalk in comparison with Configuration A. However, using the same arguments as in Configuration B above, we can see that the performance offered by Configuration C is fully acceptable for axial component measurement. In addition, this configuration minimizes the cost of strain gages and eliminates the extreme thermal sensitivity found in semiconductor gages. Therefore, Configuration C offers the more attractive alternative if Configuration A proves unworkable in practice.

4.3.6 Additional Observations from Analytical Results

We can draw a few other conclusions from the results of these analyses. First of all, we see that the use of conventional gain (1000-2000 V/V) electronics for axial force measurements would dictate the use of semiconductor strain gages with at least 3.5 VDC excitation voltage. In most cases, this value for excitation is within the region where thermal drift problems could be expected.

Secondly, in order to use conventional strain gages ($GF \approx 2.0$) ultra high gain (10,000 V/V) amplification is required in conjunction with exceptionally high excitation voltage (≥ 15 VDC). This value for gain is higher than normally used since input noise $\sim 1 \mu V$ can become significant. However, electronics of the quality required for this task is readily available at moderate cost.

In considering the effects of using excitation voltages greater than 15 VDC, one must again consider thermal drift problems. The power dissipated

by these strain gages can be written as

$$P = \frac{V^2}{R}$$

In order to operate within the limits recommended by strain gage manufacturers, power dissipation must be kept below 0.04W per gage. This results in

$$R = \frac{V^2}{P} = \frac{15^2}{.04} = 5625 \Omega$$

So, we must use ultra-high resistance strain gages in order to realize proper sensitivity. Again, though not commonplace, such gaging material is presently commercially available at moderate cost.

4.3.7 Conclusions from Analytical Results

From the considerations above we can draw the following conclusions:

1. The suggested scheme for measuring horizontal and axial components should result in satisfactory transducer performance.
2. The Transducer Configuration A for measurement of axial force offers the highest potential transducer sensitivity at the expense of higher transducer manufacturing cost and higher susceptibility to thermal drift.
3. Transducer Configuration C offers a fully acceptable axial component measurement scheme while reducing transducer cost and thermal problems. However, such a method would require the use of more sophisticated high-gain signal conditioning and infrequently-used strain gage materials. If these difficulties can be overcome, Configuration C would be the best overall solution to the axial force measurement problem.

4.4 Cost/Benefit Considerations

The first research objective of this Phase I development program was to instrument a toolholder within the constraints of reasonable cost and utility. Based on the work conducted in this feasibility program, it is anticipated that a ruggedized production instrumented toolholder would be fabricated by placing a custom designed strain element at only four locations on a modified production toolholder. The estimated manufacturing cost of such a device would be approximately \$100 in small quantities. Since such a device would be used continuously for several weeks before replacement, it would seem that the goal of reasonable cost has been obtained. Since custom strain elements can be ordered in quantity from present suppliers of strain gage rosettes, it would also appear that the instrumented toolholder could be reduced to a readily producible commodity.

The approach of utilizing custom designed strain elements will give the added benefit of allowing the location of one strain gage relative to another to be held very accurately. Therefore the time required to mount the gages accurately will be greatly reduced as only four elements will need to be located on the toolholder.

Matrix methods give an additional benefit in that any strain element alignment errors can be factored out by the matrix method. While it is desirable to locate the strain elements accurately for minimum crosstalk, matrix methods will reduce the requirement for gage placement accuracy and therefore help in making the toolholder a readily producible inexpensive product.

5. TRANSDUCER CONSTRUCTION

5.1 Description of Transducer Construction

The implementation of the foregoing transducer design involved mounting strain gages on a standard toolholder available for machines in use at AMTI. An Aloris ADS 5-3 toolholder with 5/8 in square shank was modified to receive the necessary gages. Figure 8 shows a photographic view of this construction. Four surfaces were ground flat for gage mounting. A hole (.125 in) was drilled along the axis of the toolholder large enough to allow extraction of all lead wires for the strain gage bridges. At each gage mounting surface a smaller hole (.094 in) was drilled intersecting with the axial passage to lead wiring away from the gage sites. After mounting, the gages were covered with protective foam padding and aluminum foil tape for shielding. The wiring was carried from the transducer to the signal conditioners using shielded multi-conductor cable. Fig. 9 shows a photographic view of this construction.

5.1.1 Configuration A

The first prototype constructed used standard foil-type strain gages (120 Ω , GF = 2.015, thermally compensated to steel) for positions 1-8 in Fig. 7a. Positions 9-12, those sensitive to axial loading, used semiconductor gages (120 Ω , GF = ± 100). Two of these were P-type doping (positive $\Delta R/R$ for positive $\Delta L/L$) and two were negative doping (negative $\Delta R/R$ for positive $\Delta L/L$). As described in Section 4.1, this configuration allowed measurement of a pure compressive load while retaining full bridge sensitivity. As described in Sec. 7.2, this configuration proved to have no thermal stability.

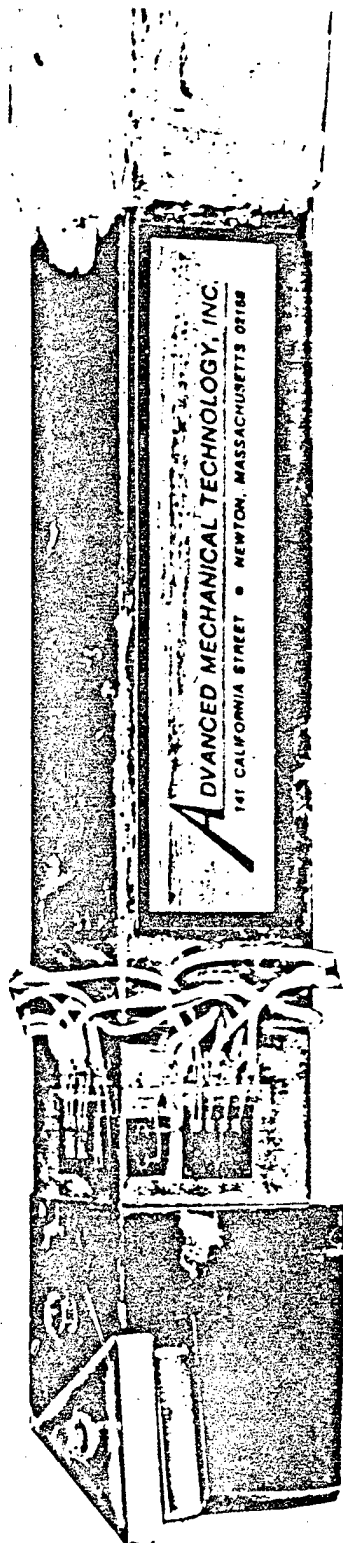


FIGURE 8: PROTOTYPE INSTRUMENTED
TOOLHOLDER TRANSDUCER

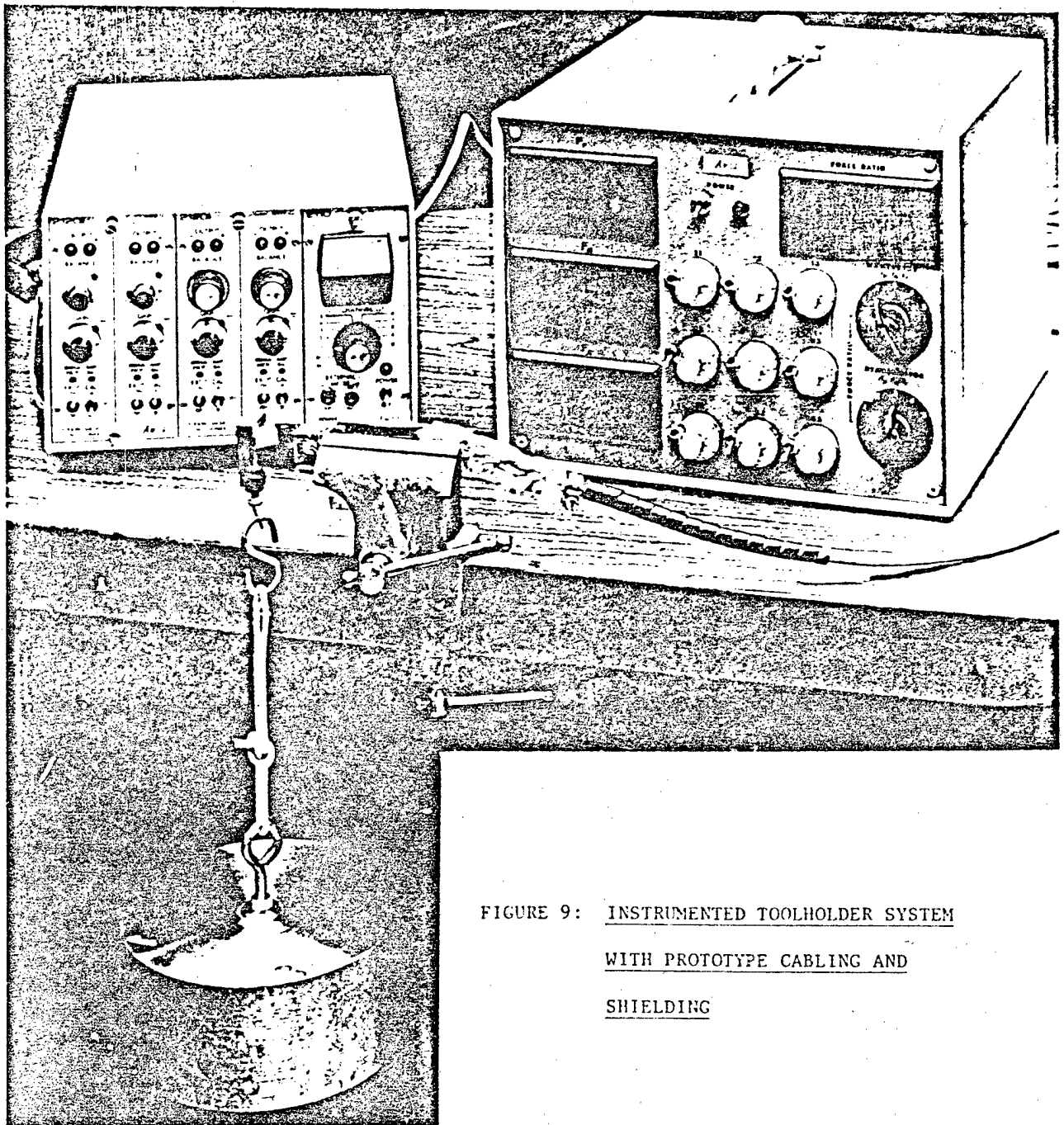


FIGURE 9: INSTRUMENTED TOOLHOLDER SYSTEM
WITH PROTOTYPE CABLING AND
SHIELDING

5.1.2 Configuration B

The second configuration used four N-type semiconductor gages (120 Ω , GF = -100, thermally compensated for steel) with two mounted perpendicular to the shank axis. This configuration permitted greater thermal stability at the expense of reduced bridge sensitivity. This configuration is pictured in Fig. 10.

5.1.3 Configuration C

Due to limitations of time and capital, Configuration C was not tested in a transducer prototype. However, a series of tests were performed to establish the viability of this configuration. The reader is referred to Sec. 7.3.3 for a summary of these brief tests.

5.2 Conclusions from Transducer Construction

This prototype demonstrates all the desired features for a satisfactory production-oriented dynamometer. It uses a standard toolholder and mounts in a standard tool post. As will be shown in later sections, it can produce accuracy and utility comparable to a research lathe dynamometer. Finally, it can be constructed for a cost low enough to permit widespread application in conventional and numeric-controlled machining operations.

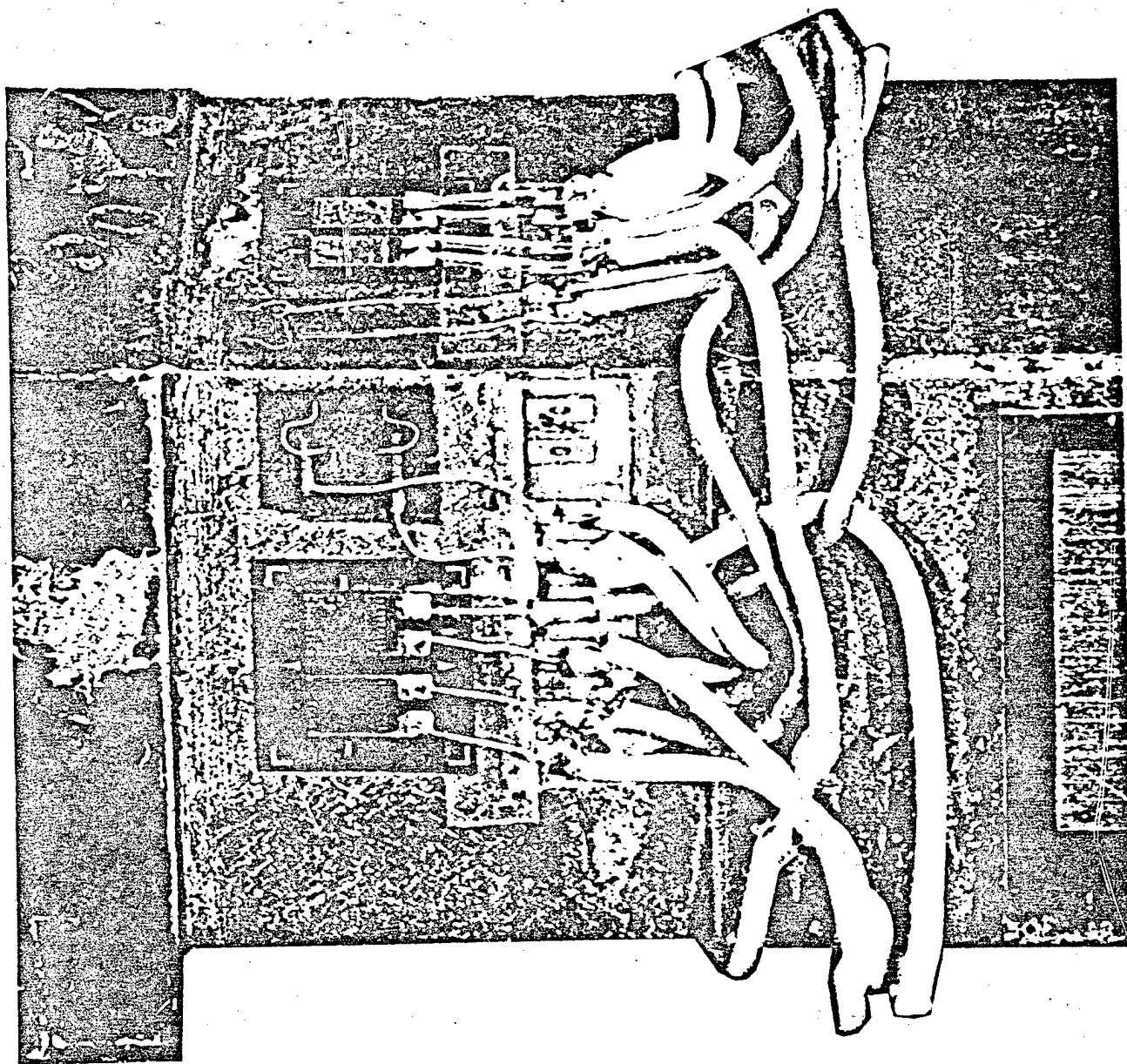


FIGURE 10: INSTRUMENTED TOOLHOLDER GAGE
PLACEMENT SHOWING AXIAL CONFIGURATION B

6. PROTOTYPE SYSTEM SIGNAL CONDITIONING AND PROCESSING

The general requirements for signal conditioning and processing can be summarized in graphic form by Fig. 11. Low-level strain gage signals must be amplified to useable voltage levels. These three signals must then be manipulated to perform the multiplication by the influence coefficients. Finally, the results must be displayed or recorded as force components with engineering units (lb, kg).

In this prototype system, bridge excitation and amplification was performed by standard strain gage signal conditioners (Vishay 2120A). This equipment provided suitable excitation and gain for all transducer testing.

The matrix manipulation was performed by an analog circuit built for this program. It represented the simplest and most straightforward means of inputting coefficients and displaying results. Even though this function could have been performed using a computer system, the analog circuit presented a solution with the simpler implementation and debugging requirements.

Fig. 12 presents a block diagram of one channel of the analog circuitry. (The detailed electronic circuit diagram is presented in Appendix C.) Influence coefficients (b_{ij}) were input using precision 10-turn potentiometers with graduated dials. The resulting signals were summed using a standard op-amp inverting-summer-circuit. The force signals were displayed on digital panel meters in engineering units (lbf). An analog dividing circuit allowed display of force ratios. Finally, any recording was done with a multichannel strip chart recorder.

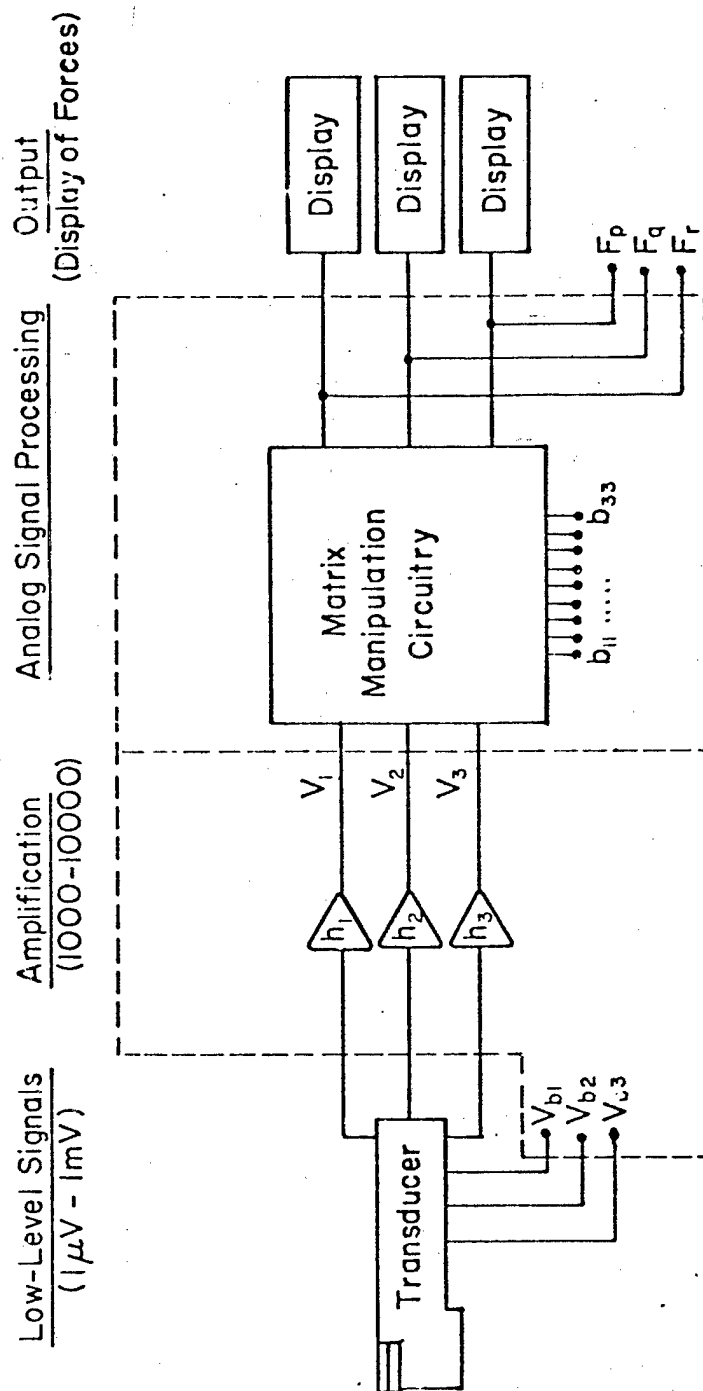


FIGURE 11: SIGNAL CONDITIONING AND PROCESSING REQUIREMENTS

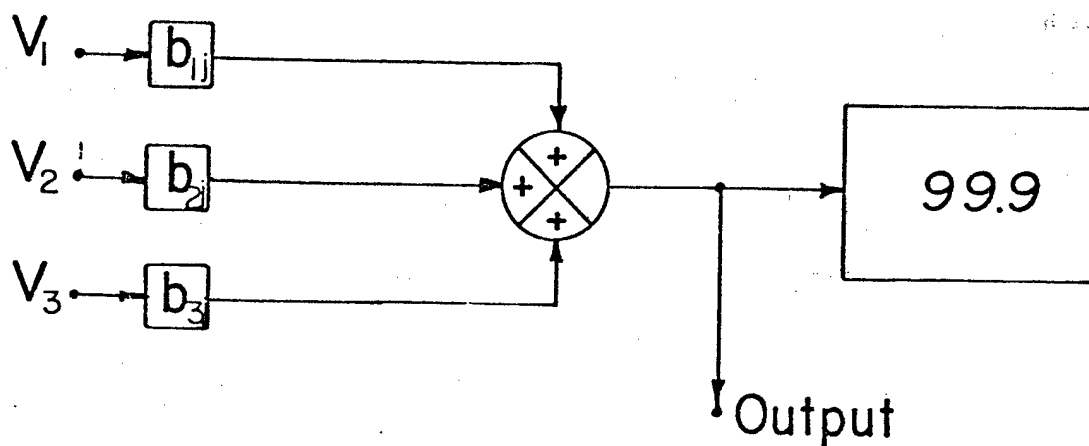


FIGURE 12: BLOCK DIAGRAM OF ANALOG
MATRIX MANIPULATION FOR
SIGNAL PROCESSING

Fig. 13 shows the prototype signal processing system. This analog circuitry performed its function in a satisfactory way. The system maintained accuracies within $\pm 1\%$ of full scale indications. Transducer calibrations were performed using the same voltage indication as used for force display. Therefore, any system errors were eliminated in the system calibration technique. A production circuit of similar design would operate well if the intended system function were force and force ratio display alone.

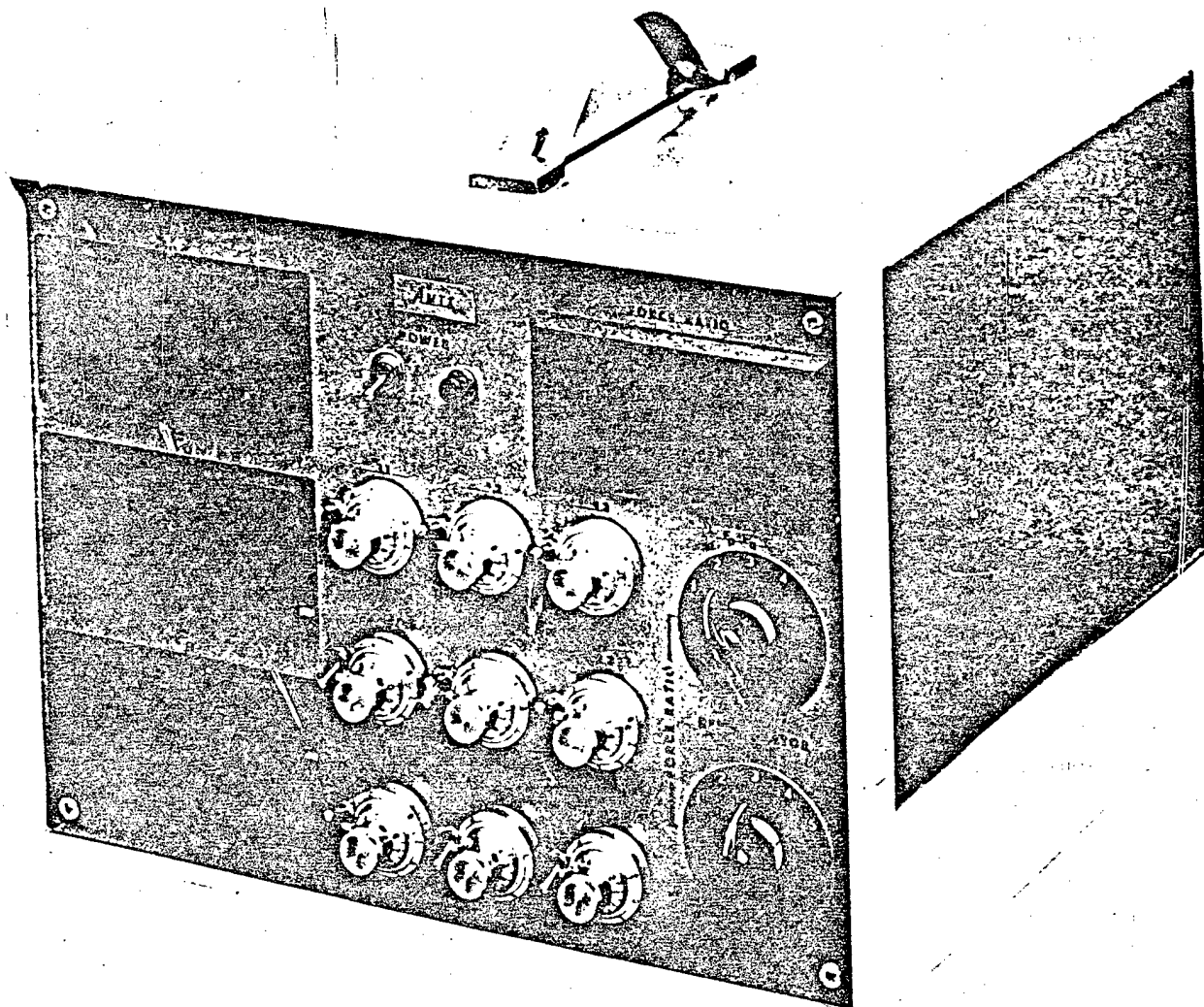


FIGURE 13: PROTOTYPE ANALOG SIGNAL
PROCESSING SYSTEM

7. TRANSDUCER TESTING RESULTS

The transducer prototype was tested using three separate techniques.

These included:

- a. Static calibration and testing
- b. Measurement of dynamic output during actual machining operations
- c. Comparison with a research lathe dynamometer during machining operations.

The first of these techniques was used to determine quantitative performance by measuring sensitivity, linearity and stability. The second and third techniques were employed to give a qualitative view of transducer performance and not to study specific dynamic characteristics.

7.1 Static Calibration Procedure

In order to determine the values for the influence coefficients for the actual transducer, a static calibration technique was used. Weights hanging from flexible connections were used to apply the horizontal, vertical and axial forces. A test fixture was constructed which simulated the application of cutting forces at a cutting point. This fixture is shown in Fig. 14. It was constructed so that three tapped holes aligned in the horizontal, vertical and axial directions passed through a single point. When attached to the toolholder, this point coincided with the top of the cutting tool.

The toolholder was then mounted in a secure position and leveled in the proper orientation, as pictured in Fig. 15. A known weight was hung

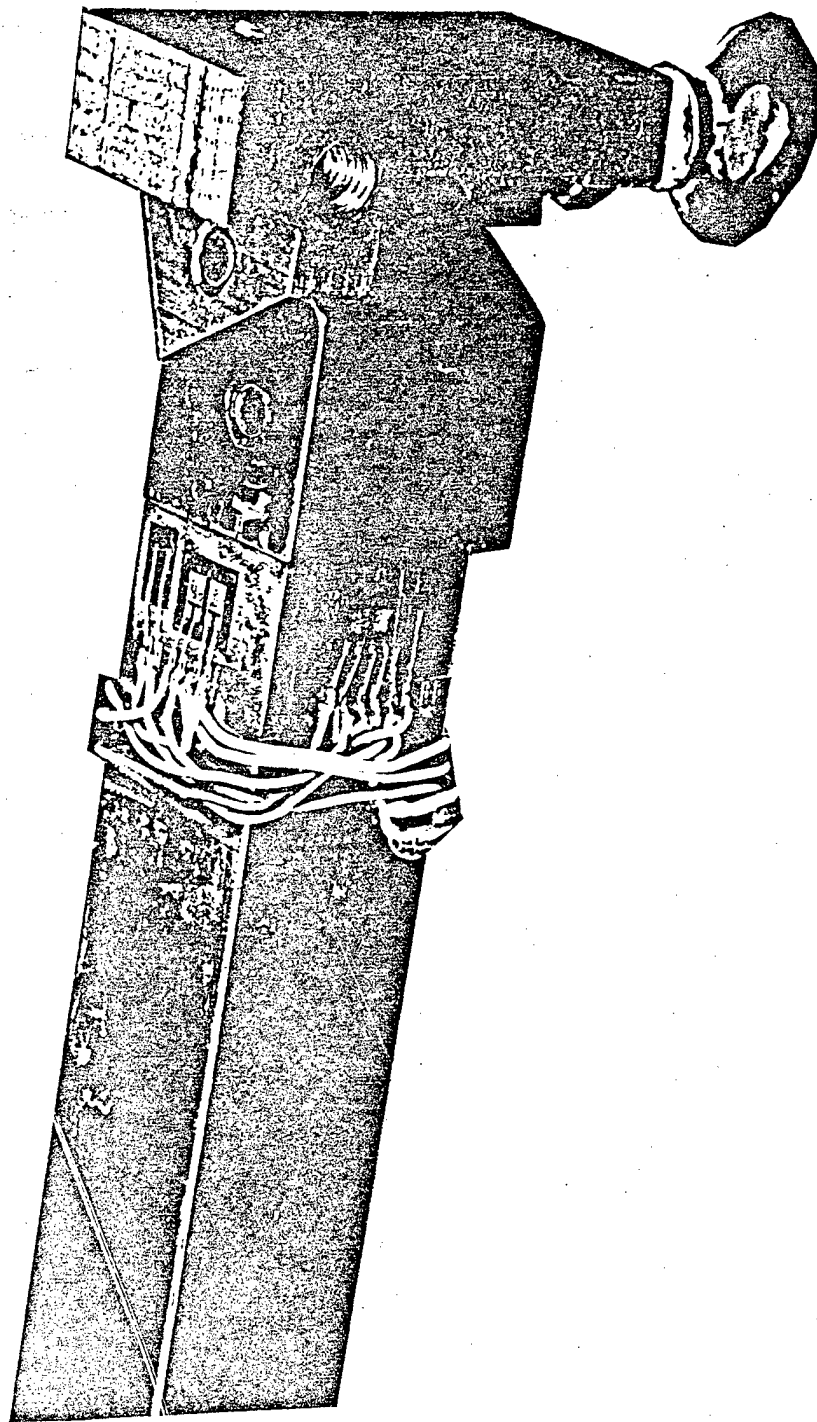


FIGURE 14: INSTRUMENTED TOOLHOLDER WITH STATIC
CALIBRATION FIXTURE INSTALLED

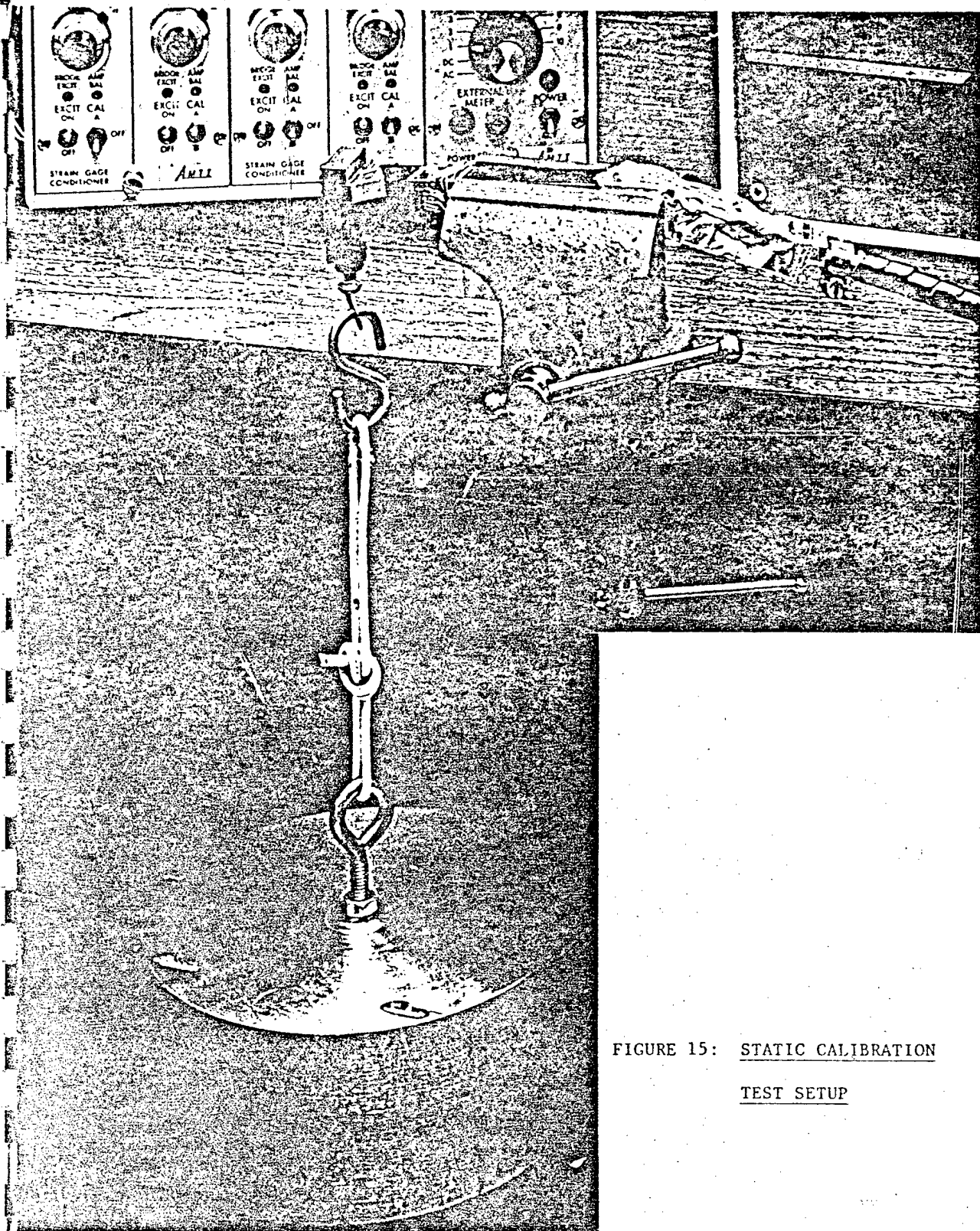


FIGURE 15: STATIC CALIBRATION
TEST SETUP

from an eyelet screwed into the proper fixture hole. The application of this test weight resulted in outputs from the three bridges, measured using the signal processing "black box". The outputs were recorded and the procedure repeated for the other two directions.

This procedure generated a set of nine numbers which related three force inputs to three bridge outputs. By dividing these recorded values by the measured weight of the test weight, a set of numbers resulted which corresponded to the B_{ij} values in the equation.

$$\begin{bmatrix} F_P \\ F_Q \\ F_R \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

Using a programmable calculator, we can invert the B matrix and arrive at the set of influence coefficients described in Equation 4.4. These coefficients were then set on the appropriate potentiometers of the Analog Signal Processing System shown in Figure 14. Values were checked for accuracy by recalibrating with the dead weights and observing the resultant forces displayed on the signal processor.

This procedure proved to be adequate for these testing purposes. In addition, it promises to be an excellent, easily performed calibration procedure for production transducers.

7.2 Measured Performance during Static Testing

Table 3 and Fig. 16 show the results of static testing performed on the instrumented toolholder prototype using Configuration B of Sec. 4.1.2.

	<u>Vertical</u>	<u>Horizontal</u>	<u>Axial</u>
Sensitivity (mV/lb)	19.4	19.6	35.2
Linearity (% FS)	1.2	1.2	3.7
Drift (mV, RTO)	0	0	20 max
Excitation Voltage (V)	5	5	3.5
Gain (V/V)	2000	2000	1000
Strain Gage Type	Foil	Foil	Semiconductor
Gage Factor	2.01	2.01	100

TABLE 3: MEASURED PERFORMANCE - STATIC TESTING

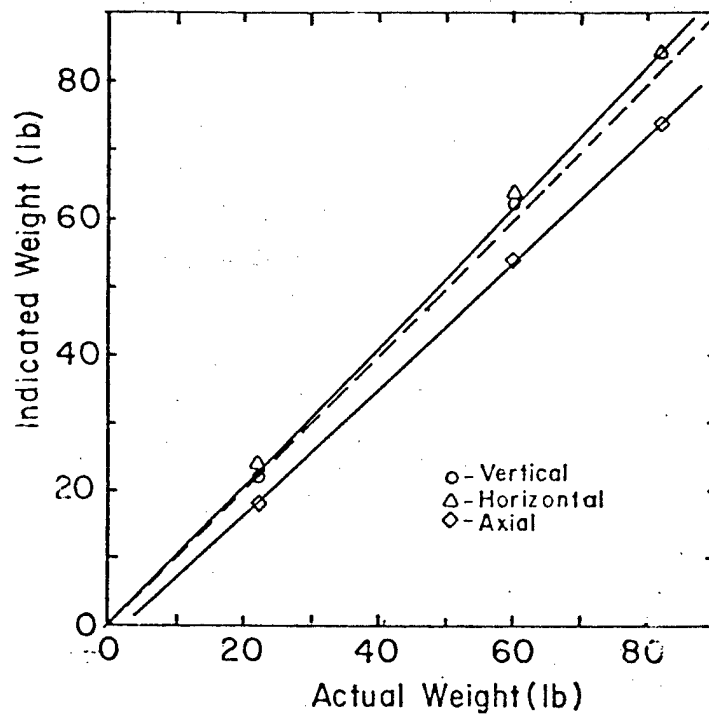


FIGURE 16: RESULTS OF STATIC
CALIBRATION TESTING

The determination of influence coefficients was performed with three different calibration weights (22, 60, 82 lb). Since the weight could be read only to the nearest pound, suitable accuracy could be obtained only using the highest weight (82 lb). Tests performed at lower weights confirmed the inaccuracies expected from display uncertainties.

The data plotted on Fig. 16 shows the linearity and zero shift of the instrument. As expected, the vertical and horizontal channels showed acceptable linearity and stability. However, the axial channel constructed with semiconductor gages revealed a lack of linearity and thermal stability even when long settling times were allowed. These results are compatible with all other qualitative observations of this semiconductor strain gage application.

7.3 Discussion of Results of Static Testing

7.3.1 Configuration A

The major technical problem encountered in this program involved the linearity and stability of the axial force component due to the semi-conductor strain gage bridge. The first prototype constructed used two P-type (positive gage factor) and two N-type (negative gage factor) semiconductor strain gages as shown in Fig 7a. This arrangement provided excellent strain sensitivity. However, as alluded to in a previous section, this arrangement showed poor thermal stability. A brief look at the characteristics of semiconductor strain gages will reveal the reasons for this thermal drift.

Fig. 17 shows the relationships for gage factor and temperature coefficient of resistance versus temperature for P-type and N-type dopings.

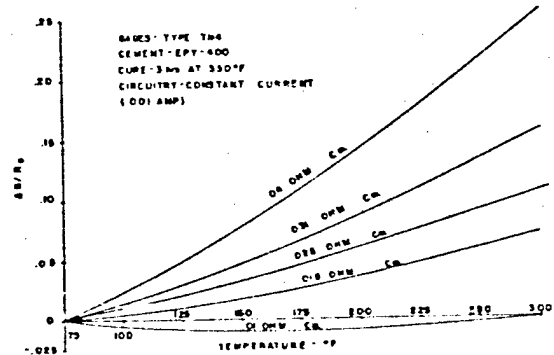
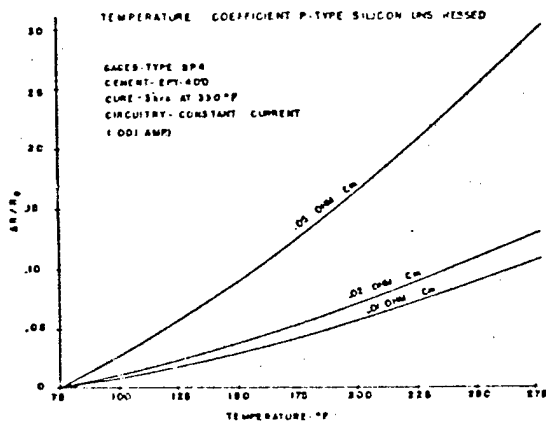
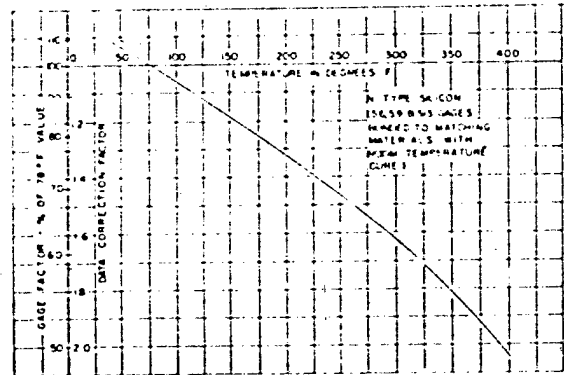
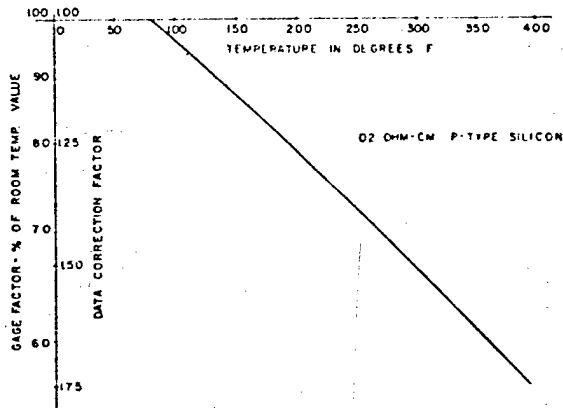


FIGURE 17: VARIATION OF GAGE FACTOR AND
TEMPERATURE COEFFICIENT WITH
TEMPERATURE FOR SEMICONDUCTOR
STRAIN GAGE MATERIALS [5].

As is apparent, these vary significantly over small temperature changes. So, for a small temperature change the N-type and P-type gages will change differently, resulting in a bridge unbalance and large apparent strain. In addition, P-type characteristics do not allow these gages to be self-compensated to particular materials (In the case of N-type gages, doping characteristics permit self-temperature-compensation.). Thus, P-type and N-type gages cannot be used in the same bridge where any even miniscule temperature variations occur.

7.3.2 Configuration B

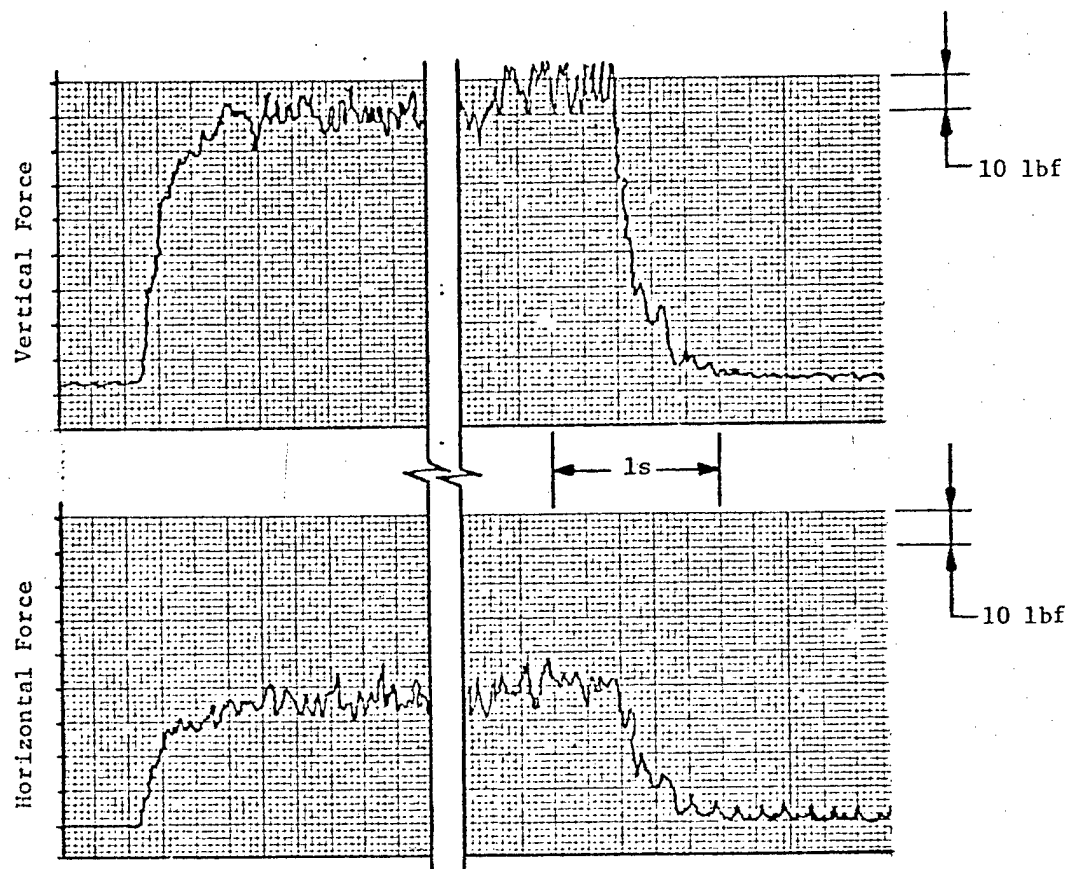
The second gage configuration, seen in Fig 7b, employed four N-type self-compensated strain gages. Two were mounted in the axial direction and two were mounted perpendicular to the axis to provide further bridge temperature compensation. As an initial check of thermal stability, this bridge was excited and the output recorded over a period of time. It was found that, as the room temperature changed by about 12°F, the bridge became unbalanced by roughly 100 mV. With a bridge sensitivity of 32 mv/lb, the net thermal error in terms of force was .25lb/°F. Thus for the large temperature excursions expected in machining operations (~100°F), we should expect thermal errors on the order of the total force indication (25 lb). Since self-compensated gages and a self-compensated bridge configuration were used, it is not apparent what caused such large thermal drift. A possible source is dissimilar bonding conditions for each gage. However, the net effect of the errors was to produce an unacceptable axial component measurement.

7.3.3 Configuration C

The limits of time and capital did not allow the construction of a prototype of Configuration C. However, in order to investigate the feasibility of using high-resistance strain gages at excitation voltages, a simple test piece was constructed. Several different bridge configurations were mounted on a 1 x 1-1/8 in block of steel. Weights were hung in a fashion identical to techniques described in Sec. 7.1. As expected, the bridges yielded outputs linear with weight. The output showed reasonable stability with 15 VDC excitation voltage applied to gages with 5K Ω nominal impedance. However, the feasibility of this strategy in an actual transducer must be determined in a later phase of work.

7.4 Measurement of Forces in Turning Operations

The prototype instrumented toolholder was tested in two separate turning operations: in a standard lathe at AMTI and in parallel measurements with a Cook research lathe dynamometer in the Materials Processing Laboratory at the Massachusetts Institute of Technology. Both sets of tests were intended to provide verification of the functionality of the transducer, not to provide a detailed study of the instrument's dynamic characteristics. In all of these tests the axial force channel was not used, since excessive thermal drift obscured the signal and introduced significant error into the other two channels. Figs. 18-20 provide two-channel traces recorded by strip chart in a number of cutting conditions. The instrument provided voltage outputs relatively free from extraneous electrical noise. In the AMTI tests, both vertical and horizontal channels showed good zero stability even in high-load, high-heat generation cases.



Conditions:

Material: Carbon Steel

Feed Rate: 0.68 ft/min

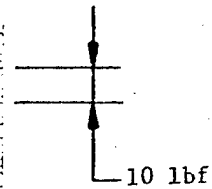
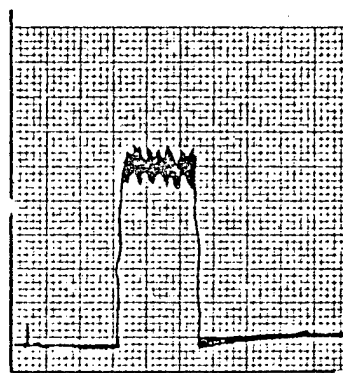
Depth of Cut: 0.030 in

Workpiece Surface Speed: 314 ft/min

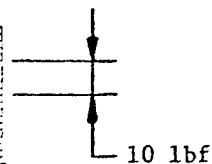
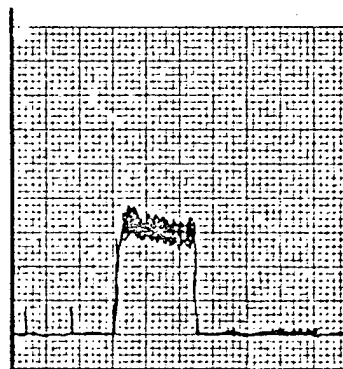
(Traces accentuated for clarity)

FIGURE 18: RECORDED OUTPUT OF VERTICAL
AND HORIZONTAL CHANNELS DURING
LATHE OPERATION AT AMTI

Vertical
Force



Horizontal
Force



time

Conditions:

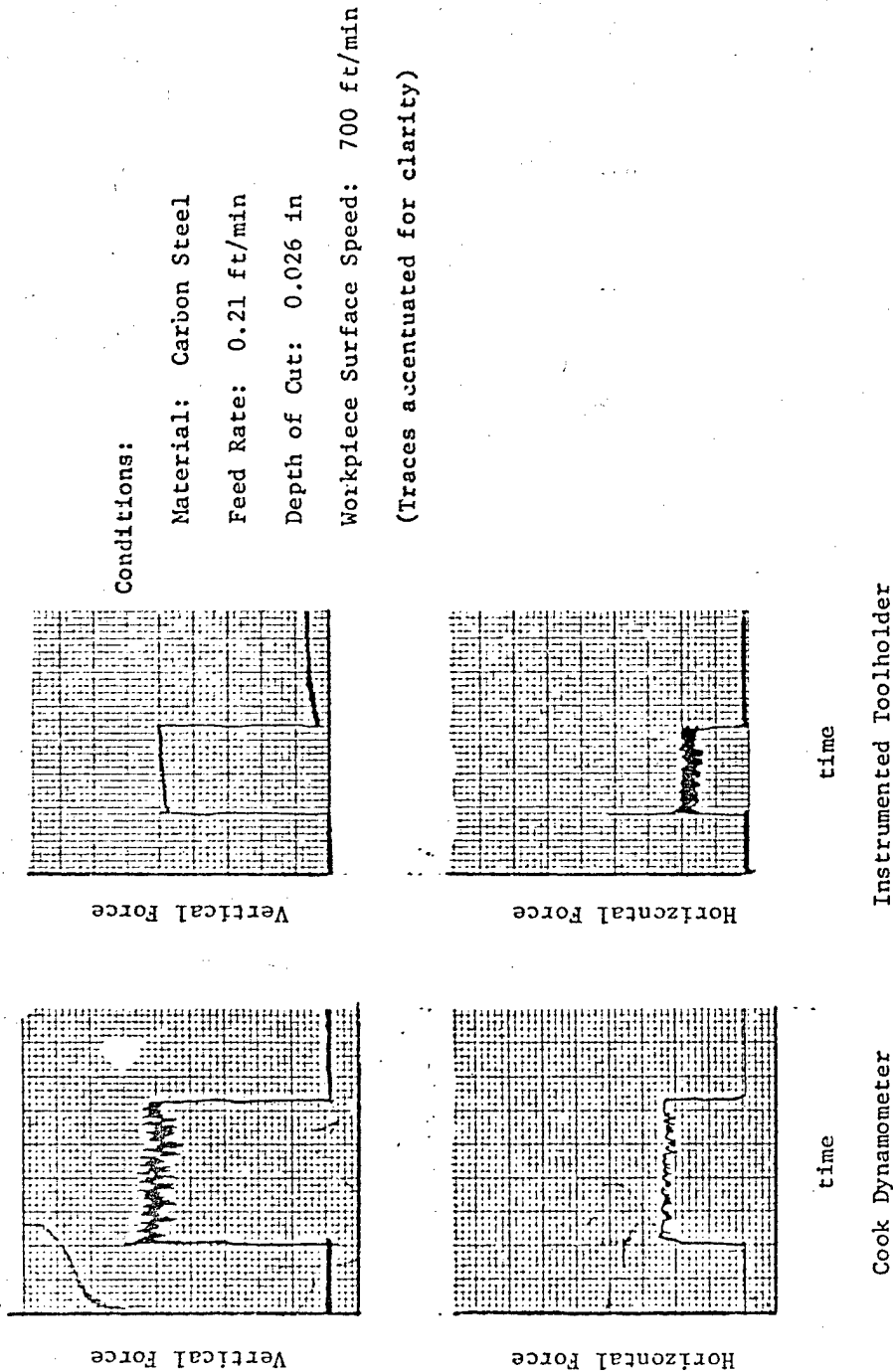
Material: Carbon Steel

Feed Rate: 0.34 ft/min

Depth of Cut: 0.040 in

Workpiece Surface Speed: 317 ft/min

FIGURE 19: RECORDED OUTPUT OF VERTICAL AND HORIZONTAL
CHANNELS DURING LATHE OPERATION AT AMTI



Conditions:

Material: Carbon Steel

Feed Rate: 0.21 ft/min

Depth of Cut: 0.026 in

Workpiece Surface Speed: 700 ft/min

(Traces accentuated for clarity)

FIGURE 20: COMPARISON OF TWO CHANNEL OUTPUTS OF INSTRUMENTED TOOLHOLDER
AND COOK DYNAMOMETER DURING LATHE OPERATION AT MIT

The MIT tests shown in Fig. 20 were performed by making a similar cut (holding surface speed, horizontal feed and depth-of-cut) on the same stock in two different situations: one with the instrumented toolholder mounted in a standard tool post; one with an identical toolholder mounted in a research lathe dynamometer. As Fig. 20 shows, the two outputs reveal similar frequency characteristics and force levels. In addition, the force ratio F_q/F_p , a characteristic tool wear parameter, is roughly the same for the two cases. So, without regarding the detailed traces, the tests show that the instrument provides vertical and horizontal force indication with clarity and accuracy comparable to a research dynamometer.

8. ADVANCED SIGNAL PROCESSING

In general, the Instrumented Toolholder System generates three signals from three strain gage bridges. The external system must perform several operations on them in order to generate system outputs which indicate three force components. These functions include

- a. amplifying signals to useful levels
- b. multiplying signals by the influence coefficients and summing products in order to obtain force indication
- c. generating an output necessary for direct or indirect observation of cutting forces.

These functions are common to any Instrumented Toolholder application. At this point several system options can be identified in order to provide input to a range of applications. At least three system options are apparent at the present time. These include:

- a. a stand-alone analog signal processing system which provides an operator with force indication and tool wear/failure indication
- b. a stand-alone microprocessor-based system which provides more sophisticated functions for an individual operator. These functions would be determined in a later research phase.
- c. A subsystem which would provide signal input to a microprocessor-based computer-numeric-control (CNC) system.

Let us now consider these three options in more detail. Option (a) is the simplest, least expensive and least flexible of the options. Such

a stand-alone "black-box" would allow force transducer retrofit to any lathe able to hold a standard toolholder. The output of this system would permit inexpensive cutting force experimentation in a small machine shop or academic community. In addition, significant research (2)(3) has shown that simple functions of cutting forces can provide an indication of tool wear and possibly prediction of tool failure. Thus, with this inexpensive device, an operator can constantly be aware of the state of his cutting tool and his margin of safety to tool failure.

The design of this system option would be very similar to the simple signal processor used for this Phase I program. It would not differ significantly from the system diagram pictured in Fig. 11. Its function would remain the same, i.e., to display the force components derived from the three transducer signals.

Option (b) provides the next level of sophistication and capability to the retrofit user. Such microprocessor capability would afford the user variable tool condition criteria for different machining environments. Such a general-purpose system would be interchangeable from machine to machine, using the same electronic package to service a variety of transducers. Though a microprocessor-based system seems more complicated and perhaps more expensive, the wide variety of electronic components available today at low cost could make the market price extremely competitive with the analog-only system. Option (b) provides an attractive application for the emerging series of "analog microprocessors".

Option (c) extends the application of the ITH into the expanding field of CNC machining. As referenced above, research efforts have shown that low-cost cutting force component measurement provides one of the most promising schemes for monitoring tool wear, tool failure prediction and even optimization of cutting processes (4). The ITH provides such a low-cost force measurement technique which is readily interfaced to any computer-based numerical control system. This system is a straight-forward application of current data acquisition techniques which present no particular implementation difficulties. The frequency characteristics and response speed of machine tool operations (~ 100 Hz) present no problem to standard data acquisition circuitry. In fact, toolholder vibrations ($\sim 5-15$ KHz) can be tracked with standard high-speed data acquisition techniques. In short, there are no foreseen barriers to the implementation of option (c) given standard, off-the-shelf microprocessor components.

The design of options (b) and (c) would be very similar. Each would possess the general requirements outlined in Fig. 21. In brief, this system would require all the usual strain gage signal conditioning circuitry. In addition, the three signals must be converted to digital form and relayed to the host microprocessor system. Once within the microprocessor, the information can be displayed for local use or stored for future use. In the stand-alone version, the only function of the computer is to perform the basic data manipulation and to display results. In the case of CNC system interface, this information must be transferred to the host computer via a communicator bus.

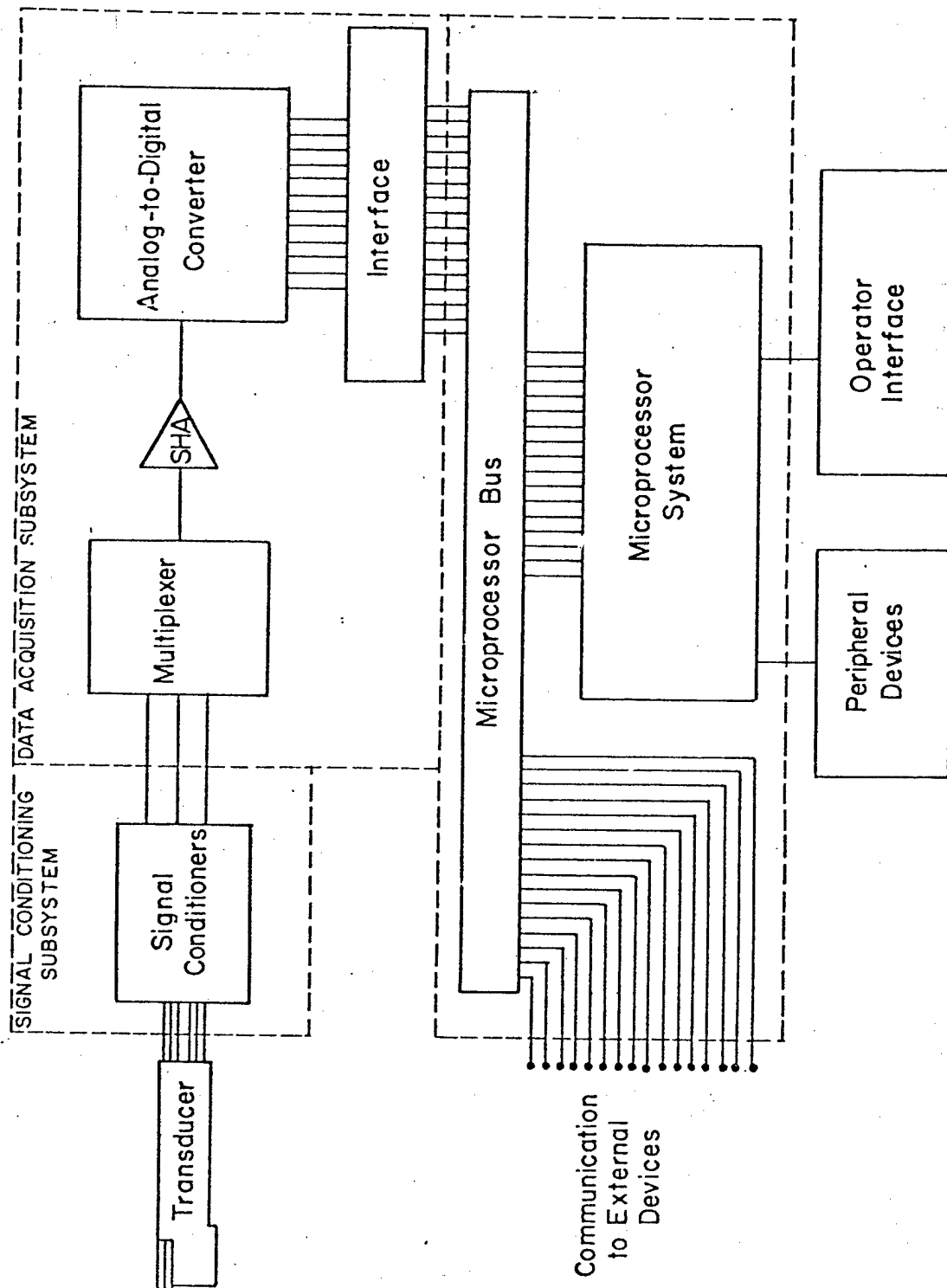


FIGURE 21: BASIC DESIGN OF DIGITAL SIGNAL PROCESSING SYSTEM

9. CONCLUSIONS

The major conclusions of this Phase I program are as follows:

1. An analytical model was developed which accurately predicts the magnitude of strain signals on an instrumented toolholder
2. A standard toolholder can be instrumented to provide accurate force signals in horizontal and vertical plane. Additional work is required to measure axial force.
3. Matrix methods for reducing mechanical crosstalk from one force to another are effective. The prototype signal processing scheme demonstrated this result.
4. Additional research is required to create a three axis instrumented toolholder and to interpret the force signals so that they are useable in an adaptive control scheme.

REFERENCES

1. Roark, R. J., Young, W. C., Formulas for Stress and Strain, McGraw-Hill, 1975.
2. Langhammer, K., "Cutting Forces as Parameters for Determining Wear on Carbide Lathe Tools and as Machinability Criterion for Steel," The Carbide Journal, May-June 1976.
3. Colwell, L. V., "Methods for Sensing the Rate of Tool Wear," Annals of the C.I.R.P., Vol. XV:V, pp. 647-651.
4. H. Takeyama, Y. Doi, T. Mitsuoka and H. Sekiguchi, Mechanical Engineering Laboratory, Japan, "Sensors of Tool Life for Optimization of Maching Advances in Machine Tool Design and Research", Proceedings of the 8th Int'l. M.T.D.R. Conference, Pergamon Press, New York, 1967.
5. Semiconductor Strain Gage Handbook, BLH Corp., Waltham, Mass, Dec. 1973.

APPENDIX A

DETAILED ANALYTICAL MODEL OF INSTRUMENTED TOOLHOLDER

A

Figure A.1 shows one method of locating gages to optimize sensitivity and minimize crosstalk. In this appendix we shall present the details of an analytical model for predicting the output of these strain gages wired in a four-arm-bridge configuration.

We shall begin by modeling this toolholder as a cantilever beam clamped a distance L from the cutting point. This beam experiences a force whose components F_p , F_q and F_r act at a point with coordinates $x = a$ and $y = c$. We begin the analysis by writing expressions for the moments about each axis as

$$\begin{aligned} M_x &= F_p l + F_r a \\ M_y &= F_r c - F_q l \\ M_z &= F_p c - F_q a. \end{aligned} \tag{A-1}$$

For each gage site we can write

$$\epsilon_n = \frac{M_y}{EI_{xx}} \frac{y_n}{x} + \frac{M_x}{EI_{yy}} \frac{x_n}{y} - \frac{F_r}{EA_{csx}} \tag{A-2}$$

where:

- x_n, y_n = x, y coordinates of each gage
- I_{xx}, I_{yy} = moments of inertia
- E = modulus of elasticity
- A_{csx} = crosssectional area of the beam

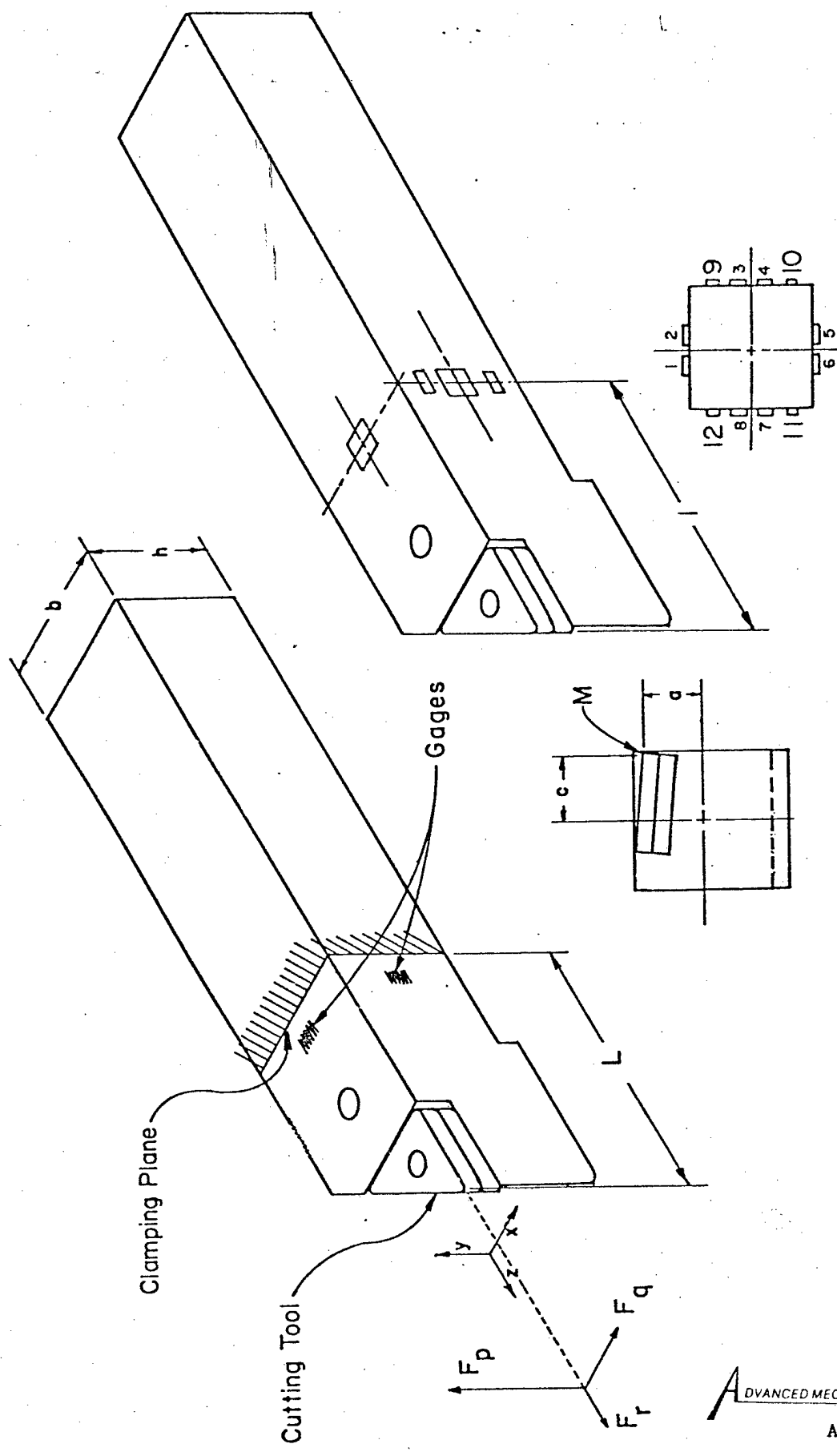


FIGURE A-1: TOOLHOLDER AND GAGE

LOCATION GEOMETRY

The first two terms on the right-hand-side are the strains due to bending moments and the third term is compressive strain due to the axial force F_r .

Substituting Equations A-1 into A-2, we find

$$\epsilon_n = \frac{(F_p l + F_r a)y_n}{EI_{xx}} + \frac{(F_r c - F_q l)x_n}{EI_{yy}} - \frac{F_r}{EA_{csx}} \quad A-3$$

Rearranging, we arrive at an expression relating each strain to the three force components.

$$\epsilon_n = \frac{ly_n}{EI_{xx}} F_p + \frac{-lx_n}{EI_{yy}} F_q + \left(\frac{ay_n}{EI_{xx}} + \frac{cx_n}{EI_{yy}} - \frac{1}{EA_{csx}} \right) F_r \quad A-4$$

Now, by choosing gage sites and toolholder geometry, we can substitute these values into Eq. A-4 and arrive at expressions relating strain at a point to three force components. As our example, we shall choose the case illustrated in Fig. A-2. There, we have twelve gages located on the sides and top of the toolholder. In this case, we have

$$\begin{aligned} I_{xx} &= \frac{1}{12}bh^3 \\ I_{yy} &= \frac{1}{12}hb^3 \end{aligned} \quad A-5$$

Substituting the values for x-y coordinates into Eq. A-4, we arrive at the following matrix expression:

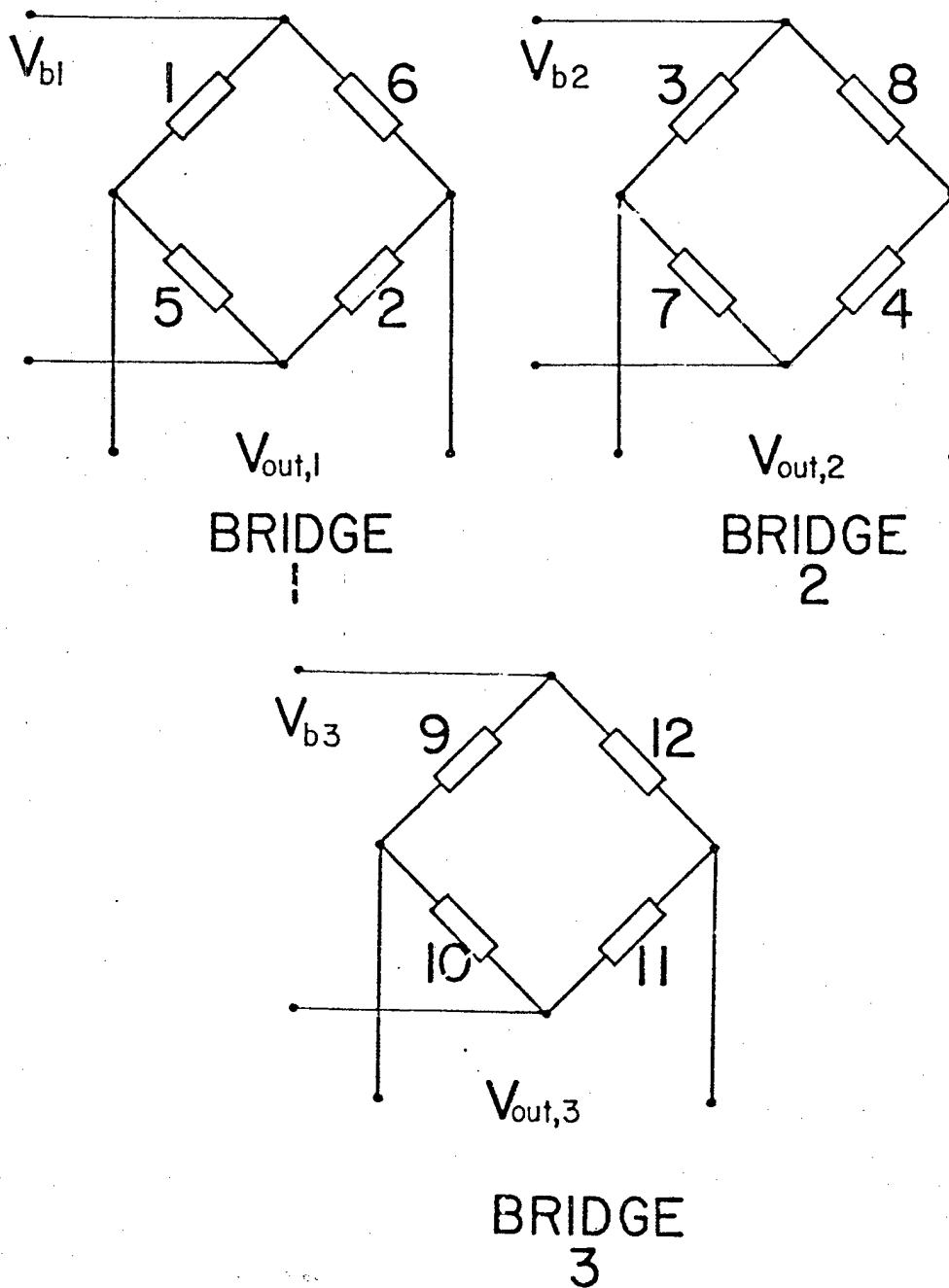


FIGURE A-2: STRAIN GAGE BRIDGE CONFIGURATIONS
FOR GAGE POSITIONS PICTURED IN
FIG. A-1.

$$\begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \\ \epsilon_7 \\ \epsilon_8 \\ \epsilon_9 \\ \epsilon_{10} \\ \epsilon_{11} \\ \epsilon_{12} \end{bmatrix} = \frac{1}{Ebh} \begin{bmatrix} \frac{-6I}{h} & \frac{-12Ix_1}{b^2} & \frac{-6a}{h} + \frac{12cx_1}{b^2} & -1 \\ \frac{-6I}{h} & \frac{-12Ix_2}{b^2} & \frac{-6a}{b} + \frac{12cx_2}{b^2} & -1 \\ \frac{-12Ix_3}{h^2} & \frac{-6I}{b} & \frac{-12y_5}{h^2} + \frac{6c}{b} & -1 \\ \frac{-12Iy_4}{h^2} & \frac{-6I}{b} & \frac{-12ay_4}{h^2} + \frac{6c}{b} & -1 \\ \frac{6I}{h} & \frac{-12Ix_5}{b^2} & \frac{6a}{b} + \frac{12cx_5}{b^2} & -1 \\ \frac{6I}{h} & \frac{-12Ix_6}{b^2} & \frac{6a}{b} + \frac{12cx_6}{b^2} & -1 \\ \frac{-12Iy_7}{h^2} & \frac{6I}{b} & \frac{-12ay_7}{h^2} - \frac{6c}{b} & -1 \\ \frac{-12Iy_8}{h^2} & \frac{6I}{b} & \frac{-12ay_8}{h^2} - \frac{6c}{b} & -1 \\ \frac{-12Iy_9}{h^2} & \frac{6I}{b} & \frac{-12ay_9}{h^2} + \frac{6c}{b} & -1 \\ \frac{-12Iy_{10}}{h^2} & \frac{-6I}{b} & \frac{-12ay_{10}}{h^2} + \frac{6c}{b} & -1 \\ \frac{-12Iy_{11}}{h^2} & \frac{6I}{b} & \frac{-12ay_{11}}{h^2} - \frac{6c}{b} & -1 \\ \frac{-12Iy_{12}}{h^2} & \frac{6I}{b} & \frac{-12ay_{12}}{h^2} - \frac{6c}{b} & -1 \end{bmatrix}$$

$$\begin{bmatrix} F_p \\ F_q \\ F_r \end{bmatrix}$$

A-6

These twelve strain gages can be wired together in three Wheatstone bridges as shown in Fig. A-2. An analysis of this bridge configuration shows that, for small strains, the bridge outputs are slightly non-linear with errors on the order of $(1/2 \epsilon^2)$. Since the strains are extremely small ($\sim 10^{-5}$), the nonlinearities become exceedingly negligible for any engineering purposes. Output from these bridges can be written

$$\begin{aligned} V_1 &= \frac{V_{b1}}{4} (S_1 \epsilon_1 + S_2 \epsilon_2 - S_5 \epsilon_5 - S_6 \epsilon_6) \\ V_2 &= \frac{V_{b2}}{4} (S_3 \epsilon_3 + S_4 \epsilon_4 - S_7 \epsilon_7 - S_8 \epsilon_8) \\ V_3 &= \frac{V_{b3}}{4} (S_9 \epsilon_9 + S_{10} \epsilon_{10} - S_{11} \epsilon_{11} - S_{12} \epsilon_{12}) \end{aligned} \quad \text{A-7}$$

where S_1 - S_{12} are the twelve gage factors and V_{b1} - V_{b3} are bridge excitation voltages.

Eq. A-6 and A-7 can be combined to yield a result of the form

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = [B] \begin{bmatrix} F_P \\ F_Q \\ F_R \end{bmatrix} \quad \text{A-8}$$

Eq. A-8, then, is a matrix representation relating three bridge outputs to three force inputs. If one were to premultiply both sides of A-8 by $[B]^{-1}$, one would obtain

$$[F] = [B]^{-1} [V] . \quad \text{A-9}$$

APPENDIX B

LISTING OF COMPUTER CODING OF
ANALYTICAL MODEL

```

00010 C***THIS SUBROUTINE CALCULATES THE INFLUENCE MATRIX
00020 SUBROUTINE AIJ
00030 COMMON /INFMAT/AMATRX
00040 COMMON/GEOM/H,L,B,A,C,E
00050 COMMON/GAGPOS/X1,X2,Y3,Y4,X5,X6,Y7,Y8,Y9,Y10
00060 REAL L,AMATRX(10,3)
00070 AMATRX(1,1)=-6.*L/H
00080 AMATRX(1,2)=-12.*L*X1/(B*B)
00090 AMATRX(1,3)=(-6.*A/H)+(12.*C*X1/(B*B))-1.0
00110 AMATRX(2,1)=AMATRX(1,1)
00120 AMATRX(2,2)=-12.*L*X2/(B*B)
00130 AMATRX(2,3)=(-6.*A/H)+(12.*C*X2/(B*B))-1.0
00140 AMATRX(3,1)=-12.*L*Y3/(H*H)
00150 AMATRX(3,2)=-6.*L/B
00160 AMATRX(3,3)=(-12.*A*Y3/(H*H))+(6.*C/B)-1.0
00170 AMATRX(4,1)=-12.*L*Y4/(H*H)
00180 AMATRX(4,2)=AMATRX(3,2)
00190 AMATRX(4,3)=(-12.*A*Y4/(H*H))+(6.*C/B)-1.0
00200 AMATRX(5,1)=-AMATRX(1,1)
00210 AMATRX(5,2)=-12.*L*X5/(B*B)
00220 AMATRX(5,3)=(6.*A/H)+(12.*C*X5/(B*B))-1.0
00230 AMATRX(6,1)=AMATRX(5,1)
00240 AMATRX(6,2)=-12.*L*X6/(B*B)
00250 AMATRX(6,3)=(6.*A/H)+(12.*C*X6/(B*B))-1.0
00260 AMATRX(7,1)=-12.*L*Y7/(H*H)
00270 AMATRX(7,2)=-AMATRX(3,2)
00280 AMATRX(7,3)=(-12.*A*Y7)-(6.*C/B)-1.0
00290 AMATRX(8,1)=-12.*L*Y8/(H*H)
00300 AMATRX(8,2)=AMATRX(7,2)
00310 AMATRX(8,3)=(-12.*A*Y8)-(6.*C/B)-1.0

```

```

00320      AMATRX(9,1)=-12.*L*Y9/(H*H)
00330      AMATRX(9,2)=AMATRX(3,2)
00340      AMATRX(9,3)=(-12.*A*Y9/(H*H))+(6.*C/B)-1.0
00350      AMATRX(10,1)=-12.*L*Y10/(H*H)
00360      AMATRX(10,2)=-AMATRX(9,2)
00370      AMATRX(10,3)=(-12.*A*Y10/(H*H))-(6.*C/B)-1.0
00380 C***MULTIPLY BY COMMON TERM
00390      DO 50 I=1,10
00400      DO 50 J=1,3
00410      AMATRX(I,J)=AMATRX(I,J)/(E*B*H)
00420      50 CONTINUE
00430      RETURN
00440      END
00450 C***THIS MAINLINE SIMPLY CALCULATES STRAINS FROM INPUTS
00460      REAL L,AMATRX(10,3),FORCE(3),STRAIN(10),ATTN(3,3),VA(3),VF(3)
00462      REAL S(10),VROUT(3)
00480 C*** AND OUTPUTS RESULTS.
00490      REAL L
00500      NAMELIST/GEOMIN/H,L,B,A,C,E,X1,X2,Y3,Y4,X5,X6,Y7,Y8,Y9,Y10
00510      NAMELIST/FORCES/FORCE/GFACTR/S/POTSET/ATTN/GAINS/H1,H2,H3
00520      NAMELIST/BRIDGE/VROUT,VB1IN,VB2IN,VB3IN
00530      NAMELIST/OUTDAT/AMATRX,STRAIN
00540      COMMON /INFMAT/AMATRX
00550      COMMON/GEOM/H,L,B,A,C,E
00560      COMMON/GAGPOS/X1,X2,Y3,Y4,X5,X6,Y7,Y8,Y9,Y10
00562      COMMON/VRATV/STRAIN,S
00580 C***READ INPUT DATA FROM FILE 10
00582      WRITE(6,8888)
00584      8888 FORMAT(' PLEASE ADVANCE PAPER TO TOP OF NEXT PAGE.....')
00586      READ(5,8889)ADUMMY

```

```

00588 8889 FORMAT(1A1)
00590 10 CONTINUE
00600 READ(10,GEOMIN,END=500)
00610 READ(10,GEOMIN)
00615 READ(10,GEOMIN)
00620 READ(10,FORCES)
00630 READ(10,GFACTR)
00640 READ(10,POTSET)
00650 READ(10,GAINS)
00660 READ(10,BRIDGE)
00670 C***DETERMINE INFLUENCE MATRIX
00680 CALL AIJ
00690 C***ZERO STRAIN MATRIX
00700 DO 50 I=1,10
00710 50 STRAIN(I)=0.0
00720 C***CALCULATE STRAINS
00730 DO 100 I=1,10
00740 DO 100 J=1,3
00750 STRAIN(I)=STRAIN(I)+AMATRX(I,J)*FORCE(J)
00760 100 CONTINUE
00770 C***CALCULATE BRIDGE OUTPUTS
00780 VBROUT(1)=VB1IN*(VRAT(1,5)-VRAT(6,2))
00790 VBROUT(2)=VB2IN*(VRAT(3,8)-VRAT(7,4))
00800 VBROUT(3)=VB3IN*((1./(2.+S(10)*STRAIN(10)))-(1.+S(9)*STRAIN(9))
00810 1/(2.+S(9)*STRAIN(9)))
00820 VA(1)=VBROUT(1)*H1
00830 VA(2)=VBROUT(2)*H2
00840 VA(3)=VBROUT(3)*H3
00850 C***ZERO OUTPUT MATRIX
00860 DO 700 J=1,3

```

```

00870 700 VF(J)=0.00000
00880 C***CALCULATE VOLTAGE OUTPUTS
00890 DO 800 I=1,3
00900 DO 800 J=1,3
00910 VF(I)=VF(I)+VA(J)*ATTN(I,J)
00920 800 CONTINUE
00930 C***OUTPUT RESULTS
00932 WRITE(6,9999)
00940 WRITE(6,GEOMIN)
00950 WRITE(6,FORCES)
00960 WRITE(6,POTSET)
00970 WRITE(6,BRIDGE)
00980 WRITE(6,GAINS)
00982 WRITE(6,2222)
00984 WRITE(6,2222)
00990 WRITE(6,1000)
01000 WRITE(6,1001)((STRAIN(I),AMATRIX(I,1),AMATRIX(I,2),AMATRIX(I,3),FORC
01010 1(I)),I=1,3)
01020 WRITE(6,1002)((STRAIN(I),AMATRIX(I,1),AMATRIX(I,2),AMATRIX(I,3)),I=4
01030 110)
01040 WRITE(6,2222)
01050 WRITE(6,1500)
01060 WRITE(6,1001)((VF(I),ATTN(I,1),ATTN(I,2),ATTN(I,3),VA(I)),I=1,3)
01062 WRITE(6,9999)
01064 9999 FORMAT(9(/))
01070 1000 FORMAT(T8,'STRAINS',T30,'INFLUENCE MATRIX',T65,'FORCES'//)
01080 1001 FORMAT(T7,E9.3,T23,E9.3,2X,E9.3,2X,E9.3,T65,F6.1)
01090 1002 FORMAT(T7,E9.3,T23,E9.3,2X,E9.3,2X,E9.3)
01100 2222 FORMAT(2(/))
01110 1500 FORMAT(T8,'SYSTEM OUTPUTS',T30,'POT SETTINGS',T65,'AMP. OUTPUTS')

```

```

01120      GO TO 10
01130      500 CONTINUE
01140      STOP
01150      END
01160      FUNCTION VRAT(I,J)
01170      COMMON/VRATV/STRAIN(10),S(10)
01176      VRDUM=(1.+S(I)*STRAIN(I))/(2.+S(I)*STRAIN(I)+S(J)*STRAIN(J))
01177      VRAT=VRDUM
01180      RETURN
01190      END
END OF DATA

```

APPENDIX C

TABULATION OF ANALYTICAL RESULTS

c

STRAINS	INFLUENCE MATRIX				FORCES
0.102E-03	-.104E-05	0.145E-06	-.365E-06		-100.00
0.893E-04	-.104E-05	-.145E-06	-.287E-06		50.00
-.335E-04	-.145E-06	-.104E-05	0.153E-06		25.00
-.609E-04	0.145E-06	-.104E-05	0.218E-06		
-.106E-03	0.104E-05	-.145E-06	0.180E-06		
-.939E-04	0.104E-05	0.145E-06	0.102E-06		
0.289E-04	0.145E-06	0.104E-05	-.338E-06		
0.563E-04	-.145E-06	0.104E-05	-.403E-06		
0.334E-05	-.536E-06	-.104E-05	0.646E-07		
-.978E-04	0.536E-06	-.104E-05	0.306E-06		
-.797E-05	0.536E-06	0.104E-05	-.250E-06		
0.932E-04	-.536E-06	0.104E-05	-.491E-06		
B-MATRIX:		-.209E-01	0.0	-.470E-02	
	0.0		-.209E-01	0.560E-02	
	0.0	0.0		-.324E-01	
F (CALC)	B-INVERSE				BRIDGE OUTPUT
-100.00	-.479E+02	0.0	0.694E+01		1.972
50.00	0.0	-.479E+02	-.827E+01		-0.905
25.00	0.0	0.0	-.309E+02		-0.810

STRAINS	INFLUENCE MATRIX				FORCES
0.102E-03	-.104E-05	0.145E-06	-.365E-06		-100.00
0.893E-04	-.104E-05	-.145E-06	-.287E-06		50.00
-.335E-04	-.145E-06	-.104E-05	0.153E-06		25.00
-.609E-04	0.145E-06	-.104E-05	0.218E-06		
-.106E-03	0.104E-05	-.145E-06	0.180E-06		
-.939E-04	0.104E-05	0.145E-06	0.102E-06		
0.289E-04	0.145E-06	0.104E-05	-.338E-06		
0.563E-04	-.145E-06	0.104E-05	-.403E-06		
0.334E-05	-.536E-06	-.104E-05	0.646E-07		
-.150E-04	0.270E-06	0.226E-06	0.241E-07		
-.797E-05	0.536E-06	0.104E-05	-.250E-06		
0.162E-04	-.270E-06	-.226E-06	0.241E-07		
B-MATRIX:	-.209E-01	0.0	-.470E-02		
	0.0	-.209E-01	0.560E-02		
	0.0	0.0	-.235E-01		
F(CALC)	B-INVERSE			BRIDGE OUTPUT	
-100.00	-.479E+02	0.0	0.957E+01		1.972
50.00	0.0	-.479E+02	-.114E+02		-0.905
25.00	0.0	0.0	-.425E+02		-0.588

STRAINS

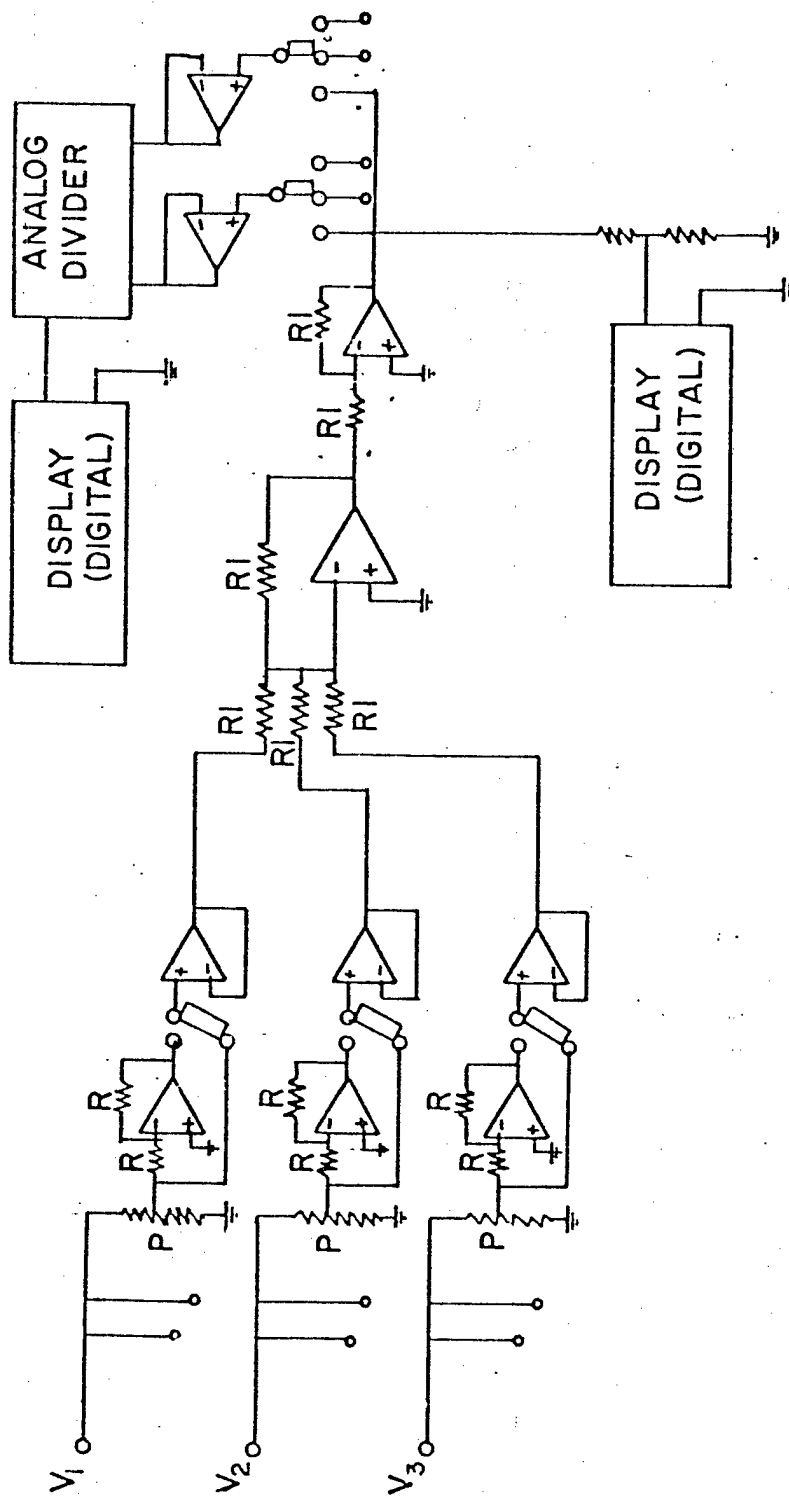
INFLUENCE MATRIX

FORCES

0.102E-03	-.104E-05	0.145E-06	-.365E-06	-100.00
0.893E-04	-.104E-05	-.145E-06	-.287E-06	50.00
-.335E-04	-.145E-06	-.104E-05	0.153E-06	25.00
-.609E-04	0.145E-06	-.104E-05	0.218E-06	
-.106E-03	0.104E-05	-.145E-06	0.180E-06	
-.939E-04	0.104E-05	0.145E-06	0.102E-06	
0.289E-04	0.145E-06	0.104E-05	-.338E-06	
0.563E-04	-.145E-06	0.104E-05	-.403E-06	
0.334E-05	-.536E-06	-.104E-05	0.646E-07	
-.150E-04	0.270E-06	0.226E-06	0.241E-07	
-.797E-05	0.536E-06	0.104E-05	-.250E-06	
0.162E-04	-.270E-06	-.226E-06	0.241E-07	

B-MATRIX:	-.209E-01	0.0	-.470E-02
	0.0	-.209E-01	0.560E-02
	0.0	0.0	-.204E-01

F(CALC)	B-INVERSE			BRIDGE OUTPUT
-100.00	-.479E+02	0.0	0.110E+02	1.972
50.00	0.0	-.479E+02	-.131E+02	-0.905
25.00	0.0	0.0	-.490E+02	-0.510



APPENDIX D: CIRCUIT DIAGRAM OF ONE CHANNEL
OF SIGNAL PROCESSING SYSTEM